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Volume 13 APRIL, 1943 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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p. & Index Journal no 3
15 no1 (Apr '45)

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The subscription price of the *Journal of Sedimentary Petrology* is $3.00 per year prepaid to addresses in the United States.

Single numbers, $1.50 each.

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $3.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

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Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 3–12,
FIGS. 1–2, APRIL, 1943

STYLOLITES: PRIMARY OR SECONDARY?

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ABSTRACT

The solution theory for the origin of stylolites has been further studied in light of the substitute "contraction-pressure" theory recently proposed by B. M. Shaub. According to his theory stylolites are a *primary* structure which originated while sediments were in the unconsolidated state from differential pressure and contraction which compelled "transfer of material by plastic flow." The solution theory holds that stylolites are a *secondary* phenomenon developed after consolidation and hardening of strata through rock removal by differential chemical solution. The preponderance of field evidence along many lines shows that stylolite-making has involved removal of rock material after lithification of the sediments and that stylolites are, therefore, a secondary phenomenon. Attention is focused upon a recently discovered occurrence of large and well-defined stylolites in sharply laminated limestone which gives no evidence of readjustment or reshaping of sediments through differential squeezing or flow. Field evidence bearing upon the timing of stylolite-making and upon the actual removal of rock at the sites of stylolites is summarized.

INTRODUCTION

After surviving nearly two decades of general acceptance by American geologists, the solution theory for the origin of stylolites is again being considered, after having been recently discarded by Shaub (1939) who offered a substitute proposal referred to as the "contraction-pressure" theory. Already in its short life Shaub's theory has been strongly opposed by Bastin (1940), Goldman (1940), and Stockdale (1939). It is now time to present a succinct summary of the fundamental elements in the problem of stylolite origin in light of further studies and new discoveries, and because of Shaub's disregard for the preponderance of commonplace field evidence in support of the solution theory such as had already been discussed in lengthy, detailed publications (Stockdale, 1922, 1926, 1936). Although the challenge of the solution theory is accepted as wholesome in avoiding stagnation in scientific thinking, Shaub's substitute hypothesis cannot be accepted.

There is no intent in this writing to reply to the many points of criticism and misinterpretations directed by Shaub toward earlier studies. Time and importance do not warrant such. Nor is there intent to analyze thoroughly all the details and implications in the theory of Shaub and to discuss the many problems of operation under the theory. Furthermore, space precludes a recapitulation of the whole stylolite problem (Stockdale, 1922; Twenhofel, 1932) and a thorough description and discussion of the phenomena in general. Many details, minor points, special examples, related features, etc., bearing on the subject must be dismissed.

This discussion is limited to those structures which are *genuine stylolites*. The issues must not be fogged by confusion between true stylolites and structures which have vague resemblances, here termed "pseudo-stylolites." Sufficient is it to show with unmistakable clarity, based upon field facts, that stylolites—true stylolites—are of *secondary* origin, rather than of primary origin as claimed by the contraction-pressure theory.

STATEMENT OF THE CONFLICTING THEORIES

The *solution theory* contends that stylolites result from differential chemical solution in hardened rock, under some pres-

sure, on the two sides of a parting of some sort (such as a bedding plane, lamination plane, suture, or crevice), the individual portions of the one side fitting into the dissolved out parts of the opposite, the interfitting taking place slowly and gradually as solution continues. According to this idea, stylolites are a strictly *secondary* phenomenon developed after consolidation and hardening of rock material—a feature that may be in the making in bed-rock today under proper conditions. The films of clay which cap the stylolite columns are regarded as largely, if not entirely, residual—the insoluble constituents left from the dissolving of the stone. The striated, "slicken-sided-appearing" sides of stylolites are attributed in part to the slippage of one solid rock column past another. According to this theory, most common-place development of stylolites would be expected in calcareous, soluble rocks, such as limestone and marble. This is borne out by field occurrences. However, the theory does not preclude the less frequent existence of the features in other kinds of strata (Stockdale, 1936). The solution idea was first suggested by Fuchs (1894) and was strengthened soon after by Reis (1901–1902). It was extensively reviewed and studied by Wagner in 1913 and further developed and crystallized by Stockdale (1922).

The *pressure-contraction* theory of Shaub (1939) holds that stylolites originate while sediments are in the unconsolidated state from differential pressure and compaction which has compelled "transfer of material by plastic flow." Accordingly, stylolites are a *primary* structure. To account for differential stresses necessary, the theory emphasizes the removal of pore water from sediments on top of an original thin, clay band to bring about volume contraction. "The proximity of plastic material on one side of a soft clay band and less plastic material under differential horizontal stresses on the opposite side establishes conditions where the more plastic material will flow into the places where the pressure is reduced. The process of compaction is under gravitational control, hence the normal direction of the transfer of material by plastic flow will be approximately at right angles to the bedding. Where the more and less plastic materials are strongly influenced by dynamic forces, the flow may be in any direction. . . . The transfer of material by plastic flow under very low differential pressure between the adjoining beds is believed to be slow, orderly and usually non-turbulent. The transfer is accomplished in such a manner that little evidence of dragging is developed, except at the contacts. This is believed to be due, in part, to the contracting action which assists in pulling the material laterally by the cohesive action between the particles as the pore water is removed. The gradual removal of pore water, and consequent gradual and continued volume contraction provide the necessary differential stresses for a prolonged transfer of material, which will continue until the stress differences become too low to overcome the resistance to plastic flow. . . . Stylolites in sandstones and in quartzite are believed to originate in the same manner and for the same reasons as outlined above for their origin in lime oozes" (Shaub, 1939, pp. 53–54). Materials referred to as being *plastic* were restricted to only those "in which the modulus of elasticity, elastic deformation or the ratio of stress to elastic strain, over a comparatively short period of time, is very low, or practically nil, under normal conditions of temperature and pressure as associated with unconsolidated sediments" (Shaub, 1939, p. 51).

THEORY VS. FIELD FINDINGS

The solution theory was rejected by Shaub partly because "it fails to meet the theoretical requirements." A considerable portion of Shaub's writing was devoted to an attack upon the mechanism of stylolite-making under this theory; the argument being that since the

theoretical requirements for solution did not seem to be completely satisfied, then stylolites could not have been so produced. It should be pointed out that although Shaub discarded the solution theory with emphasis upon its theoretical shortcomings, he *substituted* a theoretical mechanism concerning which he admitted the following: "The lack of definite quantitative data concerning the properties of fine-grained materials during compaction leaves much to be desired in the problem of stylolite genesis. Until more accurate and specific data are available, the following *tentative* outline is given to present some of the *probable* phases of the contraction-pressure theory" (Shaub, 1939, p. 53). Except for details in the cause and mechanism of operation, Shaub's theory is essentially the old pressure theory of the past century, generally discarded when the works of Fuchs, Wagner, and others appeared. It strikes the same fundamental snags.

Although there may be reason for strong disagreement with points of detail on theory proper, it is not the purpose of this writing to argue on theoretical grounds. On the contrary, it is preferable to approach the problem of stylolite origin by assembling the numerous findings from the field and to arrive at a conclusion deductively. Greatest weight should be attached to those findings which are most commonplace and subject to least question or doubt. The major deduction regarding stylolite origin should not hinge upon some doubtful feature, some rare finding, or some peculiar detail. In much geologic reasoning one is compelled to accept the undeniable facts of field evidence leading to the solving of a problem in spite of theory which might at first seem to reflect against it. A flood of field evidence shows that in the making of true stylolites solution and rock removal *did occur* in some manner or other. Shaub (1939) rigorously criticized the theoretical *how* of solution and overlooked or undervalued the evidence pointing to the *fact* of rock removal.

THE FUNDAMENTAL ISSUE

The problem of stylolite origin is resolved into this fundamental issue: are stylolites of primary or secondary origin? Were stylolites formed before the lithification of the sediments, or were they formed later, *after* consolidation and hardening? The pressure theory accounts for stylolite development at the beginning stages of rock making, when the sediment was in the soft, unconsolidated state. It establishes "the origin of stylolites prior to the consolidation of the enclosing rock" (Shaub, 1939, p. 60). It allows for *no* removal of rock substance; instead, for a readjustment and rearrangement of materials through differential squeezing or flow. It demands that the clay films associated with stylolite-seams be an original deposit in the form of a clay band rather than a secondary residuum. The solution theory, on the other hand, provides a secondary origin for stylolites. The structures were made in the already-hardened rock, with solution and removal of the rock at the sites occupied by the newly formed stylolite columns. No mashing, distortion, or reshaping of original sedimentary features would be required. Thus, it is clear that the decision on the fundamental issue hinges in considerable part upon the field evidence along two lines: (a) the time of stylolite-making, or age relationships; and (b) actual removal of rock at the place of the stylolites.

EVIDENCE OF SECONDARY ORIGIN OF STYLOLITES

The two lines of evidence just suggested are closely related; as a matter of fact, in many cases, the combination may be supported by a single type of feature. Only the more important observations will be enumerated and discussed. Many details are omitted.

The Timing of Stylolite-Making—Structural Relationships

There are numerous situations which give a clue as to the time of stylolite

origin relative to the age of the rock—observations which indicate that the stylolites are younger than the enclosing sediments and were made *after* the birth of the hardened rock.

Stylolites in Metamorphic Rocks.—Stylolites abound in marbles, and are rare even in quartzite—both, metamorphic rocks. Is one to believe that the superabundant and sharply defined stylolite-seams of marble beds were spared the ravages of nature and survived the destructive processes of metamorphism which transformed the original properties of the rock? The pressure theory demands this belief; the solution theory does not.

Stylolites Along Unconformities.—Stylolites occur along unconformities—pronounced, well-defined unconformities. A good example is at the base of the Columbus (Devonian) limestone in central Ohio. The stylolites are not miniature, questionable forms; on the other hand the columns are several inches in length. Is one to believe, as required by the pressure theory, that the material of the underlying formation retained its unconsolidated ooze state throughout thousands, if not millions of years, later to be differentially squeezed into a freshly-laid bed of soft ooze which finally came to bury the erosion surface after a thin layer of clay had first been laid down?

Stylolite-Seams Which Depart from Normal Bedding.—Although most stylolite-seams are associated with bedding and lamination planes, some are not. They have frequently been found along crevices of various sorts, joints, faults, sutures in fossils, around the margins of fossils, and the like. As a matter of fact there are instances of branching stylolite-seams and of seams cutting across one another. Is one to believe that such rock partings as joints, crevices, criss-cross fractures, etc., were initiated in the rock while the sediments were still in the ooze state, so as to allow the "plastic flow" demanded by the pressure theory, or did they come at a much later date? The pressure theory suggests that the clay associated with stylolite-seams is an original film laid down in regular order with the accumulating sediments and that through its "restraining action" has a function in the stylolite-making process (Shaub, 1939, p. 53). How can the deposition of such mud films along positions which depart markedly from the normal planes of sedimentation, to say nothing about those which are branching and criss-crossed, be reconciled with sound sedimentary principles? These situations strike no snag under the solution theory which would explain the films as residual deposits left along secondary structural partings. In fairness to Shaub, however, the following is quoted: "The development of stylolites along any other structural planes, as crevices and faults, is believed to be due to the physical conditions of the materials along these planes. The materials bordering the planes have probably been affected by the shearing action which rendered them more resistant to the free transfer of pore water from one side to the other. Any thin bed which retards the movement of pore water can function in the same manner as an interbedded clay seam during the formation of stylolites. The pore water which comes in contact with the stylolite-seams developed along crevices and faults may supply in colloidal form all the visible clay observed in such instances" (Shaub, 1939, p. 54). This is certainly vague, hard to interpret, and difficult to reconcile with Shaub's main thesis, unless the implication is that the sediments remain in the plastic state until after fracturing, faulting, etc. The last statement, concerning clay "in colloidal form" as the source of the clay films, implies that in cases of stylolites along crevices which depart from the normal bedding, the amount of clay is but slight, and that such a slight amount might be explained as deposited from a colloidal source rather than in the regular way preferred under the theory. It should be pointed out that the clay films associated with such "abnormal" stylolite-partings may be no different in kind nor amount from

those associated with regular, bedding-plane stylolites. Striking occurrences have been found of oblique, branching, and criss-cross seams where the individual stylolite columns are an inch or more in length and the associated clay films are of appreciable thickness.

Stylolites Along Faults.—These occurrences deserve special mention. Most faulting certainly succeeds rock hardening. During the past year the writer has been studying drill cores of limestones and dolomites taken at the site of the Douglas Dam, Sevier County, Tennessee, now under construction by the Tennessee Valley Authority. The strata, which are in the Valley and Ridge Province of the Southern Appalachians, were long ago subjected to great deformational stress. They have been bent, broken, and shattered. The drill cores reveal many kinds of secondary structures, including small faults and fractures. Unmistakable stylolites occur along some of them. The writer has also observed stylolites along faults exposed in quarry faces. Fault surfaces may offer easy access to the percolating ground waters, which in turn are the agent of solution in the stylolite-making process, long after the time of rock hardening.

Stylolites in Relation to Chert.—Another line of evidence bearing on the timing of stylolite-making has been pointed out by Bastin (1933, pp. 371–381; 1940, p. 216) who described the relations between cherts and stylolites in pure limestones in southwestern Missouri where the stylolites are developed in abundance and to large size. Bastin showed, "(1) that the cherts had developed by the replacement of limestones, (2) that some of the stylolites had developed *after* the cherts were formed, and (3) that some cherts had been impressed into bordering limestone *pari passu* with the growth of the stylolites in the latter." Thus, another field observation is added to the flood of evidence that stylolites were formed after the hardening of the sediments.

Absence of Stylolites in Unconsolidated Sediments.—If stylolites are formed through "transfer of material by plastic flow under very low pressure" at a time "prior to the consolidation of the enclosing rock" (Shaub, 1939, pp. 53, 60), why are they *not* found in the unindurated deposits of clay, silt, sand, etc., which are so commonplace today. Shaub (1939, pp. 58, 59) made a special point of "a type of marking noted on some of the stylolite columns and walls in the Lockport dolomite" which he called "adhesion ridges" and compared this with a similar marking which he was able to produce "in plastic Connecticut Valley varved clay with a block of wood by breaking contact with the clay." The first assumption is that the markings in the two situations are identical; the second that they could be made only in plastic material. The fundamental question is: are true stylolites, the entire structural feature, developed in the plastic sediments? Is there convincing proof that surface markings referred to require soft sediment for their making? Shaub, himself, expressed some doubt by his statement "adhesion ridges are *probably* not reproducible in a solidified material" (Shaub, 1939, p. 58).

Evidence of Rock Removal

Attention is now directed to the line of evidence which most vigorously refutes the pressure idea of stylolite origin and supports the solution theory. If the *solution theory* is correct, there must be proof of actual removal of rock material—material taken away at the places of the interfitting stylolite columns. If the *pressure theory* is correct, then there must be proof of *no* removal of material, but on the contrary, of actual squeezing, bending, and re-shaping of sediments from plastic flow induced by differential pressure. The flood of evidence in support of rock removal is so great that by no means can all of it be mentioned. In presenting it, reliance is not placed upon an occasional, rare, and exceptional find. This evidence also bears upon the timing of stylolite-making.

Impressed Pebbles (*"Gerölleindrücke"*).—A significant phenomenon which gives

evidence of rock removal long after the time of lithification of sediments is that of "Gerölleindrücke"—impressed, or pitted, pebbles in conglomerates. Many European workers have treated this problem and agreed that the pitting of one pebble at the contact with another pebble came about in many cases through solution and therefore removal of mineral matter, at the zone of contact where the pressure was applied. In this country splendid examples are seen in the "Potomac Marble," from the base of the Triassic beds in Maryland. In many instances the contact surfaces between adjoining pebbles are minutely, although unmistakably, stylolitic (Stockdale, 1936, p. 133; Bastin, 1940, p. 214). Surely the pebbles were in the solid state long before they were gathered into the conglomerate, yet the stylolite-making came still later. Rock removal, and not differential slipping of plastic ooze along the lines of contact, is demanded. This line of evidence was ignored by Shaub, and no mention was made of the writer's 1936 paper on "Rare Stylolites" in which this phenomenon, along with others, was treated.

Undisturbed Lamination Above and Beneath Stylolites.—No field evidence condemns the pressure theory more than the relationships between stylolites and the lamination of the rock above and beneath the stylolite columns. A direct question is: where stylolites occur in laminated limestone are the laminae clearly cut out and removed at places where stylolites fit into the laminated bed or are they misshaped and bent around the ends of the columns as demanded by the pressure theory? That the laminae are clearly cut away was emphasized in the writer's 1922 paper (Stockdale, 1922, pp. 55–58), and largely ignored by Shaub. Recently, however, still more striking observations have been made to give unequivocal proof of the absence of any mashing, bending, or misshaping of sediments above and beneath stylolite columns (see fig. 1). Shaub stated, "The absence of bending of beds has been used as negative evidence in support of the solution theory; consequently the presentation of an unmistakable occurrence of bending of the laminations is strong contradictory evidence against the same theory" (Shaub, 1939, p. 60). He offered a photograph of a peculiar find which he described as "a stylolite column which shows how the lamination of the rock may bend to follow the outline of the column as it moves by plastic flow into a zone of reduced pressure" (Shaub, 1939, p. 59, fig. 9). A study of the photograph immediately brings the question: "Is the structure actually a stylolite?" Certainly it is not an ordinary single, sharply-defined stylolite-column, but, instead, appears to be a bent seam which in itself may carry miniature stylolites. Furthermore, the photograph reveals no evidence of bending *above* or *below* the particular bent seam. Whereas this, apparently, was a *rare* find, the kind of situation referred to by the present writer and exemplified by the specimen illustrated in fig. 1 is not an exception; on the other hand, it is commonplace. The photograph has not been retouched. Note how clearly and unmistakably the parallel laminae carry without interruption in straight lines across the limestone both above and beneath the large columns of the major stylolite-seams. Note, furthermore, how the smaller, minor stylolite-seams occupy positions in only the alternating columns which extend downward from the bed above, in testimony of complex, multiple "stylolite-history" (discussed later). Does one question the cutting out and removal of the laminated limestone at the sites occupied by these major columns? Worthy of emphasis, furthermore, are instances of individual stylolite columns which are over one foot in length (Stockdale, 1922, p. 38), yet the rock above and beneath them reveals no evidence of distortion such as should be always obvious and unmistakable under the pressure theory of origin (See also Stockdale, 1922, figs. 23 and 24).

Penetration of Small Stylolite-Seams by Larger Stylolites.—Just as there are instances of the removal of laminae of one

bed into which the stylolite columns of the opposite have penetrated, so there are numerous examples of smaller (even miniature) stylolite-seams which have been pierced and partially eradicated by larger stylolites developed along a major solution zone (See fig. 1; also, Stockdale, 1922, fig. 25). It is conceivable that perhaps under some circumstances the secondary stylolite-seams which lie across the alternating columns of the major seams may have been developed subsequently to, or concurrently with, the main one.

Shift in the Position of Strata Accompanying Rock Removal.—Obviously in the making of stylolites through differential solution, the amount of rock dissolved must amount in thickness to at least as much as the length of the stylolite columns. Where the stylolites are very large or where there are numerous parallel stylolite-seams, the extent of rock destruction and compaction of strata must be appreciable. Uniform dissolving with extensive lateral connections could hardly be expected over any appreciable area. Consequently differential thinning and

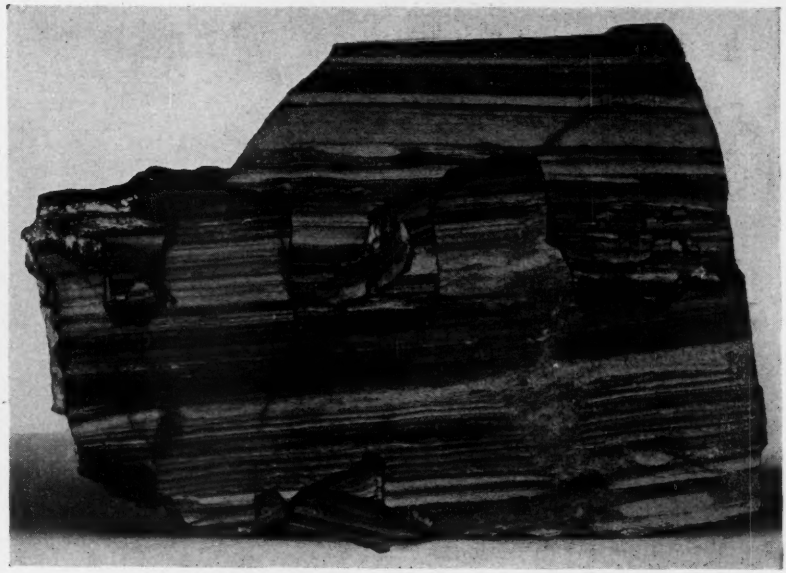

FIG. 1. Large, well-developed stylolites in laminated limestone. Note that the parallel laminae carry without interruption across the rock both above and beneath the large columns of the major stylolite-seam and that there is no mashing, bending, nor distortion of these laminae. The smaller, minor stylolite-seams, which occupy positions in only the alternating columns, give evidence of multiple "stylolite-history." The tilted segment in the middle is a remnant, bounded by stylolite-seams, whose position was shifted to accommodate adjustments and vertical thinning compelled by differential solution along the smaller stylolite zones. Note, furthermore, that the black clay "caps" are quite thick at the major stylolites and comparatively thin along the small ones. The exceptional thickness of this clay residue is because the limestone is quite argillaceous and much solution has been required to produce such large stylolites (Specimen, courtesy of Dr. E. R. Cumings, Indiana University).

compaction within the strata would result. Various stratigraphic oddities and minor structures of secondary nature should result. Certainly, there *might be* bending and tilting of layers to accommodate these adjustments, as shown in the case of the small rock segment between the secondary stylolite-seams in the middle of the specimen in figure 1. The writer has even observed minor faults caused by this kind of adjustment to rock removal (Stockdale, 1926, 1930).

Stylolites in Relation to Fossils.—Fossils which are either partially penetrated or completely pierced by stylolites are very, very common. One who has examined closely the content of the rock along the walls of individual stylolites is struck by the hundreds of small fossils, oolite grains, etc., which have been smoothed off along the contacts of columns. One column may contain but a half of a fossil, the other half is missing in the rock adjacent; or a stylolite might be encircled by a fossil which has been pierced. More striking is a single column or a whole series of sylolites which partially penetrates some *large* fossil form, as in figure 2. According to the pressure theory the missing portions of the fossils would be displaced and shoved beyond the ends of the adjoining columns. Meticulous searching by the writer has failed to reveal unequivocal evidence of such. Shaub wrote: "According to the contraction-pressure theory the corroded fossils as well as others deposited in the clay seams and the adjoining material would be carried along or within the column. . . . The *apparent* penetration of fossils by stylolites has been used as conclusive evidence that stylolites originate according to the principle of the solution theory. . . . Consequently, during the examination of stylolite occurrences in Indiana and at Lockport, N. Y., special effort was made to determine accurately the relationship of fossils to stylolites. The apparent penetration can be readily explained on the basis of the relative shearing strengths of the various shells and the unconsolidated lime ooze. The cross-sectional area of a stylolite column may be controlled wholly or in part by the outline of the shell when the shearing strength of the shell is greater than that of the surrounding material involved in, and adjacent to, the stylolite at the beginning of its formation. . . . The several parts of the sheared fossil take the cross-sectional outline of the periphery of the column" (Shaub, 1939, p. 55). Let us examine figure 2, that of a stylolite-pierced stromatoporoid. Innumerable other findings would do just as well, of corals, cephalopods, gastropods and other large forms which are but partially pierced by a battery of stylolites. Where are the displaced parts of the fossil? In what way has the *fossil* controlled the "cross-sectional area" of the stylolite columns? What evidence is there of squeezing, distortion, or rupturing of the delicate fossil structure beyond the reaches of the penetrated columns? How did the clay caps come to be deposited at the ends of the columns? Apparently realizing the weakness of the pressure theory in explaining the relations between stylolites and fossils, Shaub (1939, p. 60) rationalized further: "The penetration of fossils by stylolites is believed to be only apparent. Shells which have been deposited on the floors of seas frequently

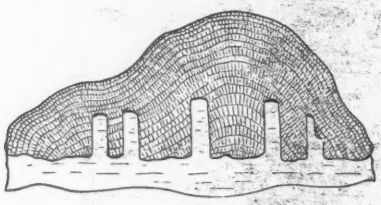

FIG. 2. Diagram of a stromatoporoid into which several stylolites have penetrated. Note that the fossil structure has been actually removed where the upward-pointing columns occur and that there has been no distortion nor rupturing of the delicate fossil structure beyond the reaches of the penetrated columns. From a specimen in The Geological Museum, Ohio State University. About one-third natural size.

contain holes and are often broken." He then concluded: "To use the apparent penetration as critical evidence in support of the solution theory, one would have to prove that the particular fossils in question did *not* contain holes prior to the development of stylolite columns which penetrate them." This means that the thousands of stylolite-pierced fossils began as shell-forms which possessed thousands of holes which were soon to become the site of stylolite columns. Is not the burden of proof reversed, that is, with the one making such a fantastic claim? Furthermore, if such were the case, why does not one find numerous "holey" fossils which did not happen to be the accidental victim of stylolite penetrations?

It should now be pointed out that many stylolite penetrations do *not* occur in the original or replaced hard parts of fossil organisms, such as shells; but, instead, in casts and molds, shell-fillings, etc. There are *secondary* features of well-known occurrence. How could the "necessary" holes have been left in such fillings to accommodate the stylolite columns? Did not such casts and molds antedate the time of stylolite-making? Microstylolites have been observed along the sutures in the molds of Endoceroid cephalopods from the Richmond beds of Ohio and Indiana. To regard these and many other similar occurrences as primary in origin is out of the question.

Other Observations

Evidence from the Clay Partings.—According to the pressure-contraction theory the clay partings associated with stylolite-seams represent a primary film of mud deposited in due turn along with the other sediments. On the other hand, if stylolites are a secondary phenomenon formed according to the solution theory, then the associated clay films are merely the solution residue. Shaub (1939) ignored the writer's extensive evidence (Stockdale, 1922, pp. 67–83) based upon chemical analyses and field observations bearing upon this point. If the clay caps of stylolites *are* a solution residue, one should expect a definite relationship between their chemical constituents and those of the limestone from which they were derived. The clay should be nothing more than a concentration of the less soluble substances of the dissolved rock. Several chemical analyses published in 1922 showed that the clays *do fulfill* all the requirements of a residual product of the limestones in which they are found. Furthermore, field studies revealed as a general rule the following: (a) the thickness of the clay caps varies in direct proportion to the length of the stylolites; (b) the thickness of the clay caps varies in inverse proportion to the purity of the limestone. These two conclusions are logical if the clay partings are the solution residue of the dissolved limestone. Where, of course, *both* the end of the penetrating stylolite column and the rock opposite have been dissolved, the length of the stylolite would not be a measure of the amount of solution and there would be a disproportionate amount of clay (Stockdale, 1922, pp. 51–53; 1926, pp. 403–405).

Rare Stylolites.—Rare stylolites are found in sandstone, quartzite, and gypsum (Tarr, 1916; Price, 1934; Stockdale, 1936). They are generally small and poorly developed. These were treated specially and were accounted for under the solution theory, in a five-page paper by the writer in 1936. Shaub (1939) failed to take account of this work and omitted references to it in his bibliography. On the other hand, he implied that the proponents of the solution theory relied upon the belief that "stylolites are limited to carbonate rocks." Perhaps, one should state, without causing any effective change in meaning, "ninety-nine per cent of all stylolites are found in carbonate rocks," such as limestone, dolomite and marble. Now, *does* the finding of stylolites in quartzite *disprove* the solution theory? Certainly the answer is *no*! Bear in mind that instances of such are extremely rare and that the structures are comparatively small and are not strongly

developed. Although solution of quartz in normal ground waters may be imperceptible as measured by laboratory experiments and observations covering but few years of time, dissolving which has gone on through the unlimited time allowed by geology should be occasionally discernible. That even quartz is slightly soluble is recognized by present-day chemists. Shaub used the occurrence of stylolites in sandstones and quartzites as evidence *against* the solution theory and in *support* of his contraction-pressure idea and stated, "Stylolites in sandstones and in quartzite are believed to originate in the same manner and for the same reasons as outlined above for their origin in lime oozes" (Shaub, 1939, p. 54). If this be the correct notion, then why are stylolites so *rare* in rocks other than those which are readily soluble? If the formation of stylolites hinges upon the *unconsolidated* condition of sediments in which there is "transfer of material by plastic flow under very low differential pressure" and if stylolites in clastic rocks originate "in the same manner and for the same reasons" as in lime oozes, then why do not sandstones and quartzites abound in stylolites? Scarcity of such stylolites militates *against* rather than supports the idea of primary origin. And, furthermore, where are the stylolites that should be in shales? Then, finally, why are there no stylolites in present-day unconsolidated sediments? The fact remains: stylolites are limited to hardened rocks and are largely confined to lime-carbonate rocks, those which are more readily soluble!

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 13–20,
FIGS. 1–2, TABLE 1, APRIL, 1943

DETRITAL MINERALS DERIVED FROM RECENT VOLCANICS IN NORTHWESTERN CHIHUAHUA, MEXICO

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ABSTRACT

The terrain drained by the Casas Grandes River and its tributaries in northwestern Chihuahua, Mexico, consists entirely of recent volcanics such as rhyolites, andesites, basalts and tuffs. The climate is arid or semi-arid. Thin sections made from rock specimens as well as river transported sediments were used to determine the characteristics and derivation of the minerals, such as feldspars and less stable ferromagnesians, are well represented in rocks from which thin sections were made but they are rarely present in the detritals. Olivine as shown in thin sections has undergone various stages of alteration which may, in part, account for the abundance of magnetite. Detrital minerals in order of abundance are quartz or chalcedony, magnetite, olivine, hypersthene, andesite, basaltic hornblende, tourmaline, mica, hematite, zircon and apatite.

INTRODUCTION

This paper presents the results of a study of the detrital sediments of the Casas Grandes River, an interior river in the northwestern part of the state of Chihuahua, Mexico. The study is of particular interest because the entire river system, including all its tributaries, flows over an igneous mantle of Tertiary extrusives. So far as known, there is no place in the drainage system where the underlying limestones and granitic rocks are exposed. Thus, the area offers unusual opportunity for study of mineral grain provenance in an arid region in which the rocks are of one general type and age.

The Casas Grandes River drains an area of approximately 18,100 square kilometers, all within the confines of Chihuahua. It lies within the Mexican Highland Section of Fenneman's (2) Basin and Range province which is characterized by "isolated ranges separated by aggraded desert plains."

The Casas Grandes River is the most western and the largest of the interior river systems of Chihuahua. It rises in the Llano de Cristo which is a plain formed on an extremely thick sequence of rhyolite flows. A few miles below its source the river has cut a deep canyon through about 2600 feet of volcanics, mainly tuffs, rhyolites, andesites and basalts. This canyon is 18 miles long. After leaving this canyon the stream flows for about 17 miles through an alluvium-filled basin to its junction with the Piedras Verdes River. This upper course of the river is also known as the San Miguel, Palanganas, Rio de Pearson and Rio de San Diego.

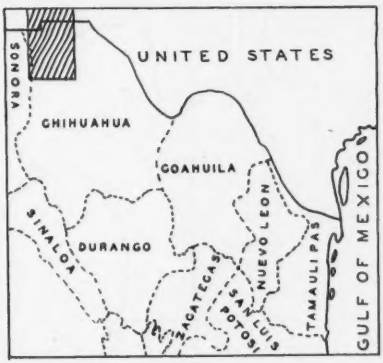

FIG. 1. Index map showing location of area.

The Piedras Verdes is the westermost tributary of the Casas Grandes River and has its source in the Sierra Madre

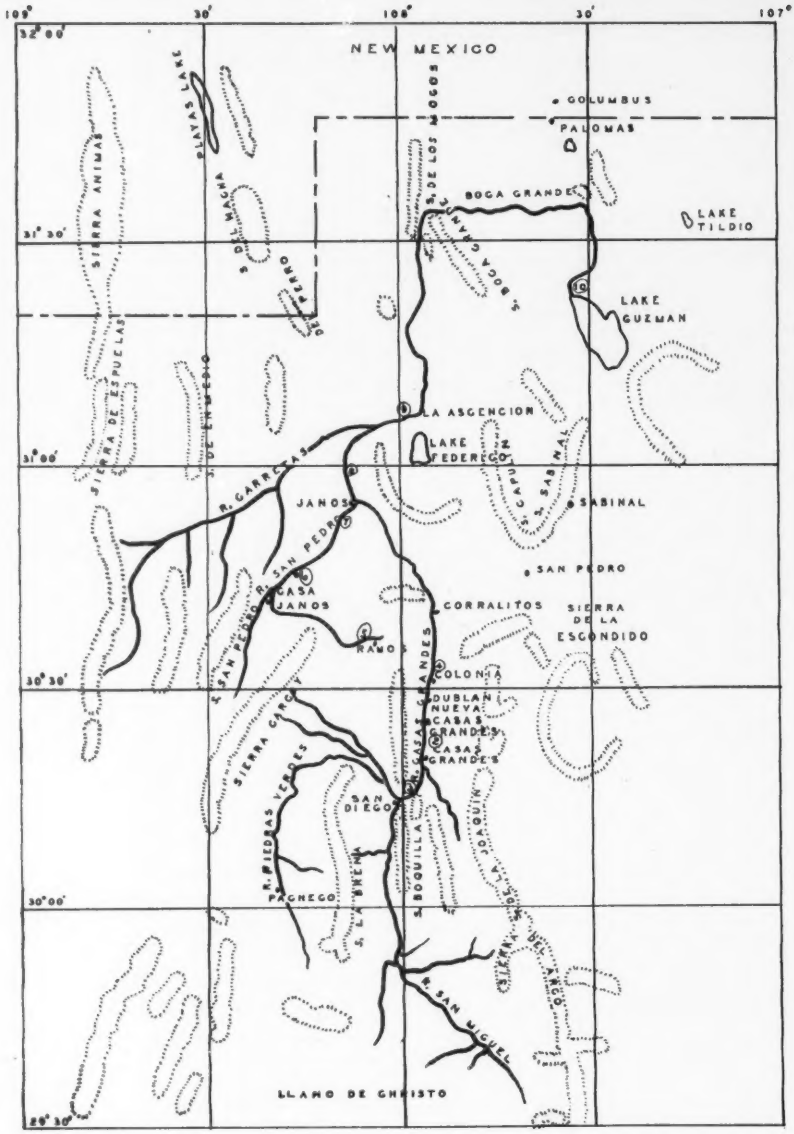

FIG. 2. Drainage basin of Casas Grandes River in northwestern Chihuahua. Scale of map 1 inch equals 15 miles. Circled numbers indicate localities from which samples were taken.

plateau near the Mormon colonies of Garcia and Pacheco. The main Piedras Verdes flows north from its source along a structural line for about 15 miles and then abruptly turns eastward and crosses the Sierra La Breña range. Below Colonia Pacheco the river has cut a deep narrow canyon through rhyolite, tuff, andesite and agglomerate. Below Colonia Juarez the Piedras Verdes enters the San Diego basin and joins the San Miguel or upper Casas Grandes to form the main Casas Grandes River. From the junction of the San Miguel and the Piedras Verdes the Casas Grandes River flows through La Boquilla, a narrow water-pass between the rhyolite tuff Cerro da la Boquilla on the south and the basaltic hills to the north, into the main Casas Grandes valley. The river flows nearly due north through the valley which is flanked on both sides by basalt-capped hills of rhyolite. Near the Corralitos railroad station small hills of columnar basalt extend westward from the Sierra Escondido. The entire valley has been filled to an unknown depth with unconsolidated materials.

Below Corralitos the Casas Grandes River flows 12 miles to its junction with the Rio San Pedro just below the town of Janos. The San Pedro heads about 50 miles back in the Sierra Madre between the Sierra Carcay on the east and the Sierra Pedro on the west. This tributary also flows through thick deposits of tuff, rhyolite, andesite and agglomerate before entering the broad valley which opens out at Casas de Janos and extends northward into New Mexico.

From Janos the Casas Grandes passes through a series of small gorges cut through the basalt flows of Quaternary age and alluvium filled basins where it divides and rejoins in a network of sloughs and channels which are usually dry for the greater part of the year. Recent basaltic lava flows at Ascencion blocked the stream and led to deposition of silt upstream from the flows. At Boca Grande the stream swings abruptly to the east as it encounters a broad basaltic lava flow extruded upon the surface of the basin fill. It flows in this direction for about 15 miles then turns south, opens out into a network of distributaries and finally empties into Lake Guzman.

CLIMATE

Northwestern Chihuahua is dominately an area with a hot dry climate. The lower portion of the Casas Grandes Basin is within the zone of 200 to 600 mm. of precipitation and falls into the desert climate (BWh) of Koeppen's (3) classification. The middle portion grades into the area of "semi-arid steppe" (BSh) characterized by richer soils, more luxuriant grass cover and a diversified creosote-mesquite vegetation. The highlands of the Sierra Madre Plateau, where most of the larger tributaries head, may be designated by the same classification as an area of, "mesothermal savannah," (Cw) and has a rainfall with an average of 650 mm. annually.

The temperature range is wide. One of Mexico's two cold poles is located in the area and the absolute minimum temperature for Mexico has been recorded at Cuidad Guerrero. In the summer temperatures are extremely high and the temperature range for a period of 24 hours may be as much as 60 degrees F. in the mountainous areas of the drainage basin. Evaporation is excessive. It is over 2,000 mm. per annum in the desert. Insolation is intense, especially during the summer months.

METHOD OF STUDY

Detrital materials representing cross sections of the stream deposits were collected from the bed of the Casas Grandes River at the following points: Vieja Casas Grandes (No. 2, Fig. 2); from a small tributary five miles above Vieja Casas Grandes (No. 3); at the Colonia Dublan Crossing on the road to Ramos (No. 4); from a tributary emptying into the San Pedro River near the town of Ramos (No. 5); from the Rio San Pedro

near Casa Janos (No. 6); from a tributary to the San Pedro one mile west of Janos (No. 7); from the Casas Grandes River below its junction with the San Pedro (No. 8); from the Casas Grandes River at Ascencion (No. 9); and from the northwestern part of Lake Guzman where the river empties into the playa lake (No. 10)

Hand specimens of the representative rocks of the lava flows were secured from outcrops adjoining the stream. Thin sections were made from these specimens. Mechanical analyses of the river sediments were made by sieving. Heavy minerals were separated by the bromoform method. Identification and characteristics of the minerals were determined with the aid of the binocular and polarizing microscopes.

GEOLOGY OF THE REGION

The quantity of lava and pyroclastic spread in this area in the Tertiary was enormous. These effusives covered the Mesozoic basement to the thickness of several thousand feet. Thayer (4) noted 19 separate lava flows in the canyons of the Aros, on the west side of the great body of extrusives known as the Sierra Madre Occidental. Between the beds of tuff and rhyolite are layers of local conglomerate derived from disintegration of the preceding flows.

The igneous mantle thins northeastward from the region of the Casas Grandes River valley and the present Juarez-Chihuahua City highway marks the eastern limit of the territory covered by the flows. These extrusives range in composition from basalt to rhyolite. Rhyolite and light colored tuffs dominate and range from 1,000 to 2,000 feet thick. Basalt is probably the most recent volcanic rock but it is not common in the upper half of the river system. In its lower half the river has cut through several basalt flows, as, for example, at Boca Grande just before it turned eastward to enter the great basin which contains the terminal lakes of the Mimbres, Casas Grandes, Santa Maria and Carmen Rivers.

The narrow basins are usually filled with conglomerates and loosely consolidated sands derived from disintegration of the Tertiary extrusives. They also contain clays, silts and eolian and colluvial soils which are the finely comminuted materials derived from the same source.

DESCRIPTION OF THE ROCKS

Rhyolite.—Most flows in the area traversed by the Casas Grandes River system are rhyolite and it is the rock that forms the bold escarpments of the mountains on either side of the river. The rock has a crude plate-like parting in the outcrops and is usually yellow to yellow-red on weathered surfaces and a pale buff on fresh surfaces. A few phenocrysts of olivine, brown biotite and feldspar are found in most occurrences. The ground mass has a dense aphanitic texture. The rhyolite of some outcrops has a light pinkish-gray color and exceptionally well developed flow structure.

Under the microscope the flow structure is very apparent. Quartz apparently does not form phenocrysts and appears only in the ground mass. The ground mass of some rhyolite is almost completely micro-crystalline with a few larger phenocrysts of olivine, brown biotite and feldspar. In others, the ground mass is glassy and vesicular with the vesicles filled with secondary chalcedony or iron oxide.

Accessory minerals are not very abundant. Olivine, altering to magnetite and serpentine along a network of irregular fractures, is common in the rhyolite but not so much so as in the basalts. Other accessory minerals include tourmaline, garnet, basaltic hornblende and occasional zircon. Sanidene is present in small quantities. Plates of strongly pleochroic brown biotite are relatively common. Some of the biotite shows alteration rims, but, most is usually fresh and unaltered. Magnetite occurs not only as an alteration product of olivine but also as in very fine particles throughout the ground mass. It is frequently altered to hematite,

thus giving some of the rhyolite a reddish color. No white micas were noted.

Secondary products in rhyolite include chalcedony, quartz, magnetite, hematite and clay minerals.

Basalt.—Basalt flows of the Casas Grandes area represent the youngest of the effusives. Some of the flows even cross pediments, *bajada* slopes, and plains formed by the erosion and deposition of the previous rhyolite and tuff extrusives.

The basalt is black to gray, as a rule, but it may be brownish or reddish if the iron minerals are oxidized. The textures are aphanitic. Some hand specimens show small phenocrysts of olivine and numerous small vesicles of which some are filled with secondary minerals.

Under the microscope most of the few phenocrysts present are olivine modified by corrosion and alteration so that the edges are rounded and the sides embayed.

The texture of the ground mass is subophitic with lath-shaped feldspars, anhedral olivine and less commonly rod-shaped crystals of basaltic hornblende. Also present in the ground mass are magnetite dust, flakes of ilmenite and rare augite. The hornblende occurs as phenocrysts with faintly corroded borders and frayed terminations. Brown biotite is present as flakes and plates and is strongly pleochroic. A transparent isotropic mineral with a high index of refraction was tentively identified as garnet but the variety is unknown. Only one or two grains were found in the thin sections.

Secondary products include iron oxide which stains the entire rock, chalcedony, quartz, calcite and clay minerals.

Andesite.—Andesite is for the most part found in the earlier flows. It ranges in color in fresh fracture from pinkish-buff to dusky red. On weathered surfaces it is usually dark brown. Hand specimens appear to be dominately glassy with few scattered phenocrysts of feldspar and biotite.

Under the microscope the texture is hyalopilitic, a felt of feldspar crystals in a glassy matrix. The ground mass is largely devitrified but most of the alteration minerals derived from the glass are so fine-grained that they show only a confused aggregate polarization under the crosses Nicols. Quartz, if present, occurs sparingly in the form of interspace filling.

Albite twins of andesine with an extinction angle averaging about 18° are very common. Andesine is usually found in sub-euhedral crystals although some are broken and irregular, and probably were formed prior to eruption.

Accessory minerals are biotite, hypersthene, olivine, orthoclase, and microscopic accessories as zircon, iron oxides and rare garnets.

Alteration products include magnetite, quartz, kaolin, chalcedony and calcite.

Volcanic tuffs.—The term "tuff" is here used for a group of rocks whose prevailing color ranges from light red to grey. They are in part breccias and in part water-lain during times of volcanic abatement. Tuffs are almost always aphanitic although some layers contain quantities of angular igneous rock fragments. They occur interbedded between layers of rhyolite and in some parts of the area attain considerable thickness.

Under the microscope the matrix is mostly devitrified glass with an index of refraction less than that of Canada balsam. Distributed throughout are small isolated grains of quartz, magnetite dust, and microlites of feldspar. In a few sections outlines of glass shards are faintly visible.

Secondary constituents consist of clay minerals, quartz, chalcedony and iron oxides.

DETRITAL MINERALS

Quartz (*Chalcedony*).—Angular fragments of chalcedony make up the largest part of the river detritals. It is difficult to distinguish from quartz except under the polarizing microscope where it shows typical aggregate structure. The fibers are arranged more or less concentrically and are alternately length-slow and length-fast. Dendritic inclusions and turbid clouds are very common in the grains

seen in reflected light. Chalcedony is derived from rhyolites, andesites and basalts where it occurs as secondary silica in cavities.

Grains of crystalline quartz are common. Most are extremely angular but occasional water-clear crystals with double terminations are present in all size ranges from 1/64 mm. to 2 mm. Sharply defined inclusions of garnet, zircon, gas bubbles, smaller quartz crystals and long acicular crystals with strong birefringence are common. Euhedral quartz crystals occur as inclusions within chalcedony and also in cracks and cavities in the igneous rocks.

Feldspar.—Sanidine occurs as water-clear grains that are difficult to distinguish from quartz in reflected light. Under the polarizing microscope sanidine can be recognized by its low relief, greyish-white interference color and by an extremely small axial angle. Cleavage is perfect parallel to (001), less perfect parallel to (010). Sometimes sanidine can be recognized under reflected light by its cleavage. Sub-rectangular cleavage fragments distinguish it from the angular grains of quartz associated with it in the light suite.

Orthoclase is similar to sanidine but may be recognized by the presence of cloudy alteration products through the grains.

Feldspars are surprisingly rare in the detritals. They comprise about .2 of one per cent of the total light separate. Sanidine is derived from the rhyolite flows. Orthoclase occurs in andesites, rhyolites, and sparingly in the basalts.

HEAVY MINERALS

Magnetite.—Magnetite is the most abundant of the heavy minerals. Most of the grains are fragmental, a few are partially rounded and a small percentage are euhedral. Magnetite ranges in color from iron-black to silver-grey. Broken surfaces show metallic luster. Surface alteration to hematite is evident on some of the grains. Magnetite is present in the stream sediments throughout the entire course of the river, but it is most abundant immediately below the junction of the San Pedro and Casas Grandes rivers. There is a marked decline in the abdundance of magnetite from Ascencion to the mouth, Lake Guzman.

Garnet.—Two varieties of garnet, yellow and red, are represented. The yellow variety is abundant but red garnet is rare.

Yellow garnet is weakly magnetic and ranges in color from light-yellow to golden-yellow. Most of the grains are irregular fragments with conchoidal fracture. Some are sub-rounded and some have the surface slightly pitted. Small dark colored inclusions are abundant. The majority of the grains are isotropic, a few show anomalous strain figures and weak anisotropism.

The garnet is derived from rhyolite, andesite, and as inclusions in other minerals.

Hypersthene.—This mineral occurs as olive-green fragments with uneven fracture. It has a vitrous luster and is weakly magnetic. Most grains are found as broken prisms with frayed ends closely resembling augite. Pleochrism ranges from pink to green of varying intensity. Dark colored inclusions are common. The mineral lacks a well-defined schiller structure. Extinction is parallel in most cases and relief is high. The figure is biaxial with a large axial angle. Hypersthene is a common mineral in the Casas Grandes River sediments. It is derived from the andesite flows.

Tourmaline.—Black and brown varieties of tourmaline are present; the latter is rare. Black tourmaline is opaque to semi-transluscent. Under the polarizing microscope the color is dark-grey in the translucent grains. This mineral is highly pleochroic and has the characteristic parallel extinction of the tourmaline group. Striations are present on some of the elongated fragments. Good crystal terminations are rare. All of the grains show vitrous luster and fragments exhibit conchoidal fracture. Cleavage is obscure. In respect to the total number of heavy

minerals tourmaline is not abundant. Tourmaline is derived from rhyolite.

Olivine.—Olivine occurs as irregular fragments that vary in color from yellow-green to olive-green. The mineral is colorless in thin sections. It is non-pleochroic and fragments show bright interference colors. Most of the grains contain dark iron inclusions. Under the high power objective olivine shows alteration to magnetite and a brownish-red mineral resembling iddingsite. Olivine is well represented in the Casas Grandes River sediments because of the proximity of basaltic source rock.

Basaltic hornblende.—Basaltic hornblende occurs chiefly as brownish-red, elongaged fragments with frayed ends. Most grains show vitrous luster and good cleavage, a few show prismatic striae. Basaltic hornblende is faintly pleochroic with color ranging from dark-brown to pale-brown, has high relief, and strong birefringence. The extinction angle is near zero. Inclusions, resembling zircon, are present in a few grains.

Biotite.—Biotite is present in brownish-red, moderately magnetic, hexagonal tablets. The particles possess strong birefringence but interference colors are masked by the color. The optic axis is small and there is a pseudo-uniaxial figure. Thin sections are strongly pleochroic. Inclusions of zircon and magnetite were noted in one specimen. No pleochroic halos were noted. Biotite is unaltered, as a rule, although a few grains show a greenish color that may be due to alteration. Biotite is present as phenocrysts in rhyolite, andesite and tuff.

Hematite.—Hematite is present in the heavy mineral assemblage as reddish-brown earthy grains with a fibrous texture. Fracture is irregular. Thin sections, if ground below .03 mm. in thickness, show faint diffused pelochrism. Hematite is a common mineral and is probably formed by the alteration of magnetite.

Zircon.—Zircon represents a very small percentage of the heavy mineral total. Purple and colorless varieties are found. It occurs as well developed crystals and subeuhedral fragments broken along inclusion planes. Crystal habit varies but prisms elongated in the direction of the principal axis and terminated by pyramidal faces are most common.

Optically zircon may be identified by high relief, high order interference colors and parallel extinction. Well defined zoning was observed in several specimens. Transparent forms show elongated bubble-like cavities, liquid and microlite-like prismatic crystals of a transparent colorless mineral having a lower index of refraction than zircon. Many of the grains contain inclusions of a reddish mineral. These in some cases are so numerous that

TABLE 1. *Abundance in per cent of heavy minerals in respect to total number at each locality.*

Mineral	2	3	4	5	6	7	8	9	10
Magnetite	62.2	14.6	75.3	71.9	77.4	90.2	73.8	38.6	77.0
Yellow Garnet	1.1	10.2	2.5	12.0	1.0	3.5	2.1	8.3	4.2
Red Garnet	.1	.1	.2	.4		.2	.3	.4	.4
Black Tourmaline	5.4	8.7	3.0	3.4	4.2	.8	5.3	8.2	4.2
Brown Tourmaline		.2	.6	.5	.3		.3	.5	.5
Olivine	9.7	27.3	4.5	1.9	5.0	.3	4.7	16.1	3.8
Hypersthene	7.7	23.3	2.5	1.9	3.2	.3	7.7	14.1	3.7
Basaltic Hornblende	2.9	11.7	2.7	3.8	4.2	.4	1.3	3.0	1.6
Hematite	1.8		3.0	1.8	1.6	2.3	1.2	3.1	3.2
Mica	8.2	3.8	3.5	1.7	2.5	.1	1.6	2.0	.6
Purple Zircon	.4		1.5		.2	.8	1.4	3.0	.4
Transparent Zircon	.4		.5	.6	.2	1.0	.2	2.5	.3
Apatite	.1	.1	.2	.1	.2	.1	.1	.2	.1

they render the crystals almost opaque. Most zircon particles have a diameter range below ½ mm. Zircon is derived from rhyolite, andesite, and from inclusions in chalcedony and biotite.

Apatite.—As a heavy mineral apatite is of minor importance in the detritals of the Casas Grandes River. Only a few grains were found among the heavy minerals. Apatite was not found in any thin section.

Apatite occurs as a salmon-pink to colorless grain with high relief and weak birefringence. The colorless grains exhibit the typical egg-shape of apatite detritals but larger grains are quite fresh and angular.

CONCLUSIONS

1. The entire area drained by the Casas Grandes River in northwestern Chihuahua, Mexico, consists of recent volcanics (rhyolite, andesite, basalt and tuff). Degradation of this terrain is taking place in a climate characterized by limited rainfall and a wide temperature range.

2. Feldspars and the less stable ferromagnesian minerals, although present in relatively large amounts in thin sections made of the rocks, comprise but a small part of the detrital material of the stream sediments. It is assumed that the feldspars have altered into clay minerals and other materials. Olivine, even in thin sections, shows various degrees of alteration to magnetite. This alteration is probably one reason why the magnetite is so abundant in the stream detritals.

3. The following is a summary of the origin of the minerals found in the detrital material of the Casas Grandes sediments:

Magnete from basalt and rhyolite.
Garnet from rhyolite and andesite.
Hypersthene from andesite.
Tourmaline from rhyolite.
Olivine from basalt.
Basaltic hornblende from basalt and andesite.
Biotite from rhyolite, andesite, tuff and basalt.
Hematite from alteration of magnetite.
Zircon from rhyolite and from inclusions in quartz grains.
Quartz mostly as a secondary product of the alteration of rhyolite, andesite, tuff and basalt.
Apatite may be derived from rhyolite although none was seen in the thin sections.
Feldspars from rhyolite, andesite, tuff and basalt.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 21–27,
APRIL, 1943

A PIPETTE METHOD OF SIZE ANALYSIS FOR THE CENTIFRUGE

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ABSTRACT

An equation is derived which gives the relation between the time required for sedimentary particles to settle out a specified distance in the tubes of a microcentrifuge and the radius of the particles. This is done by substituting into Stokes' Law the centrifugal force incurred by particles in the spinning microcentrifuge for the gravitational force incurred by particles falling freely through water.

Several sediments with average sizes in the $\frac{1}{16}$–$\frac{1}{8}$ mm. or $\frac{1}{32}$–$\frac{1}{16}$ mm. Wentworth grade are analysed by the pipette method of Krumbein and Pettijohn. Then the remaining portions of dispersed sediments are analysed for the finer grades by the pipette method of size analysis for the centrifuge. As derived in this paper it consists of an application of the Krumbein and Pettijohn method on a smaller scale to a microcentrifuge, allowing it to spin for periods of time determined by the centrifuge equation. The results obtained by the pipette-centrifuge method are compared with the results obtained on the finer grades of the same sediments by the ordinary pipette procedure of analysis. A noticeable check is evident.

A complete procedure for the size analysis of fine grained sediments is presented. The portion above $\frac{1}{16}$ mm. is screened, the portion between $\frac{1}{16}$ mm. and 1/256 mm. is analysed by the ordinary pipette method, and the grades below 1/256 mm. are analysed by the pipette-centrifuge method. In this way a great saving of time is obtained for the analysis of the finer grades of sediments.

One of the earliest applications of the centrifuge for the size analysis of sediments was in 1904 by Briggs, Martin and Pearce. Their method was simple and without the complications of the later developments. It lacked, however, the accuracy of the later methods. It consisted of centrifuging the silt and clay portion of a sedimentary dispersion until the silt had completely settled out. No times were determined for separating the silt and clay portions. The material was merely centrifuged until a microscopic check showed that no more silt was in suspension.

In 1926 Svedburg became interested in the subject and derived mathematically an equation which gave the relation between the velocity of settling of sedimentary particles in a centrifuge tube and the amount of centrifugal force that was acting upon them when the centrifuge was in motion. He also worked out a method of analysis and applied it to a study of the size frequency distribution of the particles in gold paint.

P. D. Trask in 1930 used Svedburg's equation to determine the times required for various grades to separate out in his centrifuge and developed a rather complex method which indirectly measures size distribution by studying the turbidity of sediment suspensions after they have been centrifuged for a certain time.

One of the latest advances occurred in 1934 when Steele and Bradfield applied the pipette method of Krumbein and Pettijohn (Krumbein, 1938, pp. 166–172) to the centrifuge and thus obtained a more direct approach to the problem. Essentially, their method is the same as that of this article. There are, however, several differences which will be pointed out in the appropriate places in this article. The most important difference between the Steele and Bradfield investigations and the following is that in the former no attempt was made to check the

results obtained by the centrifuge with an analysis of the same samples by the older, more established gravity-settling pipette method. Hence, no originality of invention can be claimed for the following statements, but they are claimed to be the result of independent research by the writer without reference to earlier works. The necessary mathematical background was also derived independently.

The first approach to the problem under consideration must of necessity be mathematical. How much centrifugal force sediment particles are subjected to when they are in suspension in a centrifuge tube, the rate at which they settle out and other factors must be taken into consideration. The simplest and most direct procedure for the size analysis of fine sediments is the pipette method of Krumbein and Pettijohn (Krumbein and Pettijohn, 1938, pp. 166–172). Stokes' law, proposed in 1851, is the basis for this method. It states that

$$v = \frac{2}{9}(d_1 - d_2)\frac{gr^2}{n},$$

where d_1 is the density of a sphere settling under the influence of gravity through a homogeneous liquid, d_2 is the density of the fluid, g is the acceleration due to gravity (980 cm. per sec. per sec.), r is the radius of the sphere, and n is the viscosity of the fluid. Since the pipette method is used to analyse grades in a sediment finer than .061 mm. in diameter, it is evident that all particles smaller than that size are assumed to be spheres. The error that enters due to this assumption is claimed to be not very large by Krumbein and Pettijohn.

The assumption must be made that a particle being centrifuged is subject only to centrifugal force. Since this is so much larger than gravitational force, the pull of gravity upon the particle may be neglected. Suppose than that the centrifugal acceleration a of a particle in a spinning centrifuge is substituted for g. By definition

$$a = w^2R,$$

where w is the angular velocity in radians and R is the distance of the particle from the axis of rotation. By definition

$$w = 2\pi N,$$

where N is the number of revolutions per second. Substituting the value for a into Stokes' law, we have

$$v = \frac{2}{9}(d_1 - d_2)\frac{w^2Rr^2}{n}.$$

Letting

$$C = \frac{2}{9}(d_1 - d_2)\frac{w^2}{n},$$

we have

$$v = CRr^2.$$

But for the centrifuge, v is the velocity with which the particle being centrifuged travels away from the axis of rotation, or in other words, the rate at which R is increasing.
Hence

$$\frac{dR}{dt} = v = CRr^2$$

or

$$\frac{dR}{R} = Cr^2dt.$$

Integrating, $\log_e R = Cr^2t + K$, where K is a constant of integration. Let R be R_1 when the centrifuging starts and R_2 when it is finished, remembering that R is the distance of the particle from the axis of rotation of the centrifuge. Then if t is 0, K is $\log_e R_1$ and

$$\log_e R = Cr^2t + \log_e R_1.$$

But R is R_2 at the end of a certain time of spinning t. Hence

$$\log_e R_2 = Cr^2t + \log_e R_1.$$

This may be written as

$$t = \frac{1}{Cr^2}\log_e\frac{R_2}{R_1}.$$

Letting

$$C' = \frac{1}{C}\log_e\frac{R_2}{R_1},$$

we have a simplified form of the equation as

$$t = \frac{C'}{r^2},$$

which shows essentially the time required for sedimentary grains to settle out in a centrifuge tube is inversely proportional to the square of their radius, assuming that they are perfect spheres. This equation is the necessary equation for size analysis by the centrifuge, and was derived by Svedburg in 1926, who used a different notation. This derivation was worked out independently by the writer; and it must be pointed out that it is really only an adaptation of Stokes' law, which fact Svedburg does not point out in his article.

A microcentrifuge was used in these investigations. As clocked by a tachometer, its speed was 1670 revs. per minute. Hence

$$w = 2\pi N = 174.9 \text{ radians per second.}$$

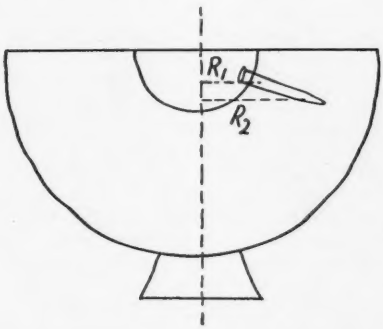
Letting d_1 be the specific gravity of quartz (2.65) and d_2 be the specific gravity of water, and n the viscosity of water at 20° C., we have

$$C = \frac{2}{9}(d_1 - d_2)\frac{w^2}{n} = 36.43 \times (174.9)^2$$

or

$$C = 1{,}114{,}100.$$

When the centrifuge was first used, at full speed, the tubes were inclined to the horizontal as shown in the sketch:



As measured, R_1 was 3.85 cm. and R_2 was 8.85 cm. Hence

$$C' = \frac{1}{C}\log_e\frac{R_2}{R_1} = \frac{1}{1{,}114{,}100}\log_e\frac{8.85}{3.85}$$

or

$$C' = 1.0056 \times 10^{-6}.$$

Using this value and the equation $t = C'/r^2$, the following table was worked out:

Time Required	*Diameter in Millimeters*
1 min. 19 sec.	1/512 mm.
5 min. 11 sec.	1/1024 mm.
20 min. 45 sec.	1/2048 mm.

This table means, for example, that it requires 1 min. 19 sec. for all grains in the suspension contained in the centrifuge tube to settle below the point marked R_2 that were larger than 1/512 mm. in diameter. It is evident then that in the first studies made, the tubes were treated as though they lay horizontally when the centrifuge was at full speed.

One of the purposes of these studies was to compare the results of analysing a sediment by means of a centrifuge with the results obtained by analysing the same sediment with the pipette method of Krumbein and Pettijohn. It is not the intention of the article to explain the pipette method as an excellent discussion of it may be found in the *Manual of Sedimentary Petrography* (Krumbein, 1938, pp. 166–172). The following time rates are taken from p. 166 of that publication:

Time Required	*Diameter in Millimeters*
8 hrs. 10 mins.	1/512 mm.
16 hrs. 21 mins.	1/1024 mm.
65 hrs. 25 mins.	1/2048 mm.

The much larger times required are at once evident.

Accordingly, the following procedure was worked out for analysing the size grades of sediments below 1/512 mm. in diameter. First the sediment was dried and screened with a series of screens based upon the Wentworth grade scale (Krumbein, 1938, p. 80). Next the material finer than .061 mm. in diameter was placed in a 1000 ml. graduate and about

a gram of sodium oxalate added to act as a dispersive agent for any colloidal material that might be present. Distilled water was added to the 1000 ml. mark, and the suspension shaken thoroughly. If after standing over night the suspension showed no signs of flocculation, it was analysed down to the less than 1/2048 mm. grade by the pipette method. If flocculation was present, further sodium oxalate was added or the suspension was heated almost to boiling. These additional dispersive procedures were usually effective.

The centrifuge used in these studies contained four five milliliter tubes. Hence after the pipette analysis was completed on a particular suspension, the 1000 ml. graduate was thoroughly shaken, and three minutes later a 20 ml. sample was extracted at a depth of 10 cm. By that time the currents due to the shaking had disappeared. This sample was divided among the four 5-ml. centrifuge tubes, and the centrifuge was spun for 1 min. 19 sec. At the end of this time the machine was braked by placing the hands on both sides of it. In this way the error due to allowing the centrifuge to come to a stop of its own accord was avoided. (In the Steele and Bradfield method no attempt is made to brake the machine at full speed. Instead the time is taken from the moment it is turned on to the moment it is turned off.) At the point corresponding to R_2 a 1 ml. sample was extracted from each of the 4 tubes. This 4 ml. sample was dried and weighed to the nearest tenth of a milligram by means of an ordinary quantitative balance, and the weight of sodium oxalate that would be present in 4 ml. of the 1000 ml. suspension was subtracted from this net weight. The result was multiplied by 250. This gives the amount of material in the whole suspension that is smaller than 1/512 mm. in diameter. Next, one ml. of distilled water was added to each of the four 5 ml. tubes and the centrifuge spun for 5 min. 11 sec. The same procedure was followed as for the first extraction. This gave the amount of material in the whole suspension that was smaller than 1/1024 mm. in diameter. By subtracting it from the amount of material finer than 1/512 mm. in diameter, the weight of sediment in the 1/512 to 1/1024 mm. grade is determined. Using this procedure, the 1/1024 to 1/2048 mm. grade was determined, and of course the less than 1/2048 mm. grade. The following results were obtained for the first sample analysed:

Grade	*Per Cent by Centrifuge*	*By Pipette*
greater than 1/512 mm.	.936%	.453%
1/512–1/1024 mm.	1.041%	.793%
1/1024–1/2048 mm.	.205%	.793%
less than 1/2048 mm.	1.020%	1.163%

No relation between the two sets of results is observable. Several other fine sediments were analysed in the same way, but these are representative results, and the others obtained exhibit nothing of note.

It was realized at this point that to extract 1 ml. from each of the 5 ml. centrifuge tubes and then to add 1 ml. of distilled water in order to bring the meniscus in the tube back to the point R_1 for the extraction of the next lowest size would radically alter the viscosity of the suspension and hence change the value of C' in the centrifuge equation. Therefore another fine sediment was analysed first by the pipette method. Then the suspension was shaken thoroughly as before, and 3 minutes later a 20 ml. sample was extracted with a pipette. This was centrifuged for the 1/512 mm. size, and the extractions from each tube made with the 1 ml. pipette as before. Then the contents of the tubes were discarded and a new 20 ml. sample extracted from the 1000 ml. suspension after 3 minutes and at 10 cm. as before. This was divided among the 4 centrifuge tubes and centrifuged for the 1/1024 mm. size. The same was done for the 1/2048 mm. size. In this way the viscosity of the portions being centrifuged would remain the same. The following results were obtained:

Grade	Per Cent by Centrifuge	By Pipette
greater than 1/512 mm.	.0924%	.630%
1/512–1/1024 mm.	.7519%	.630%
1/1024–1/2048 mm.	.1544%	.634%
less than 1/2048 mm.	2.432 %	1.537%

A rough correlation is observable.

An adjustment was made on the centrifuge which allowed the tubes to swing out to a horizontal position when the machine was in motion. By arbitrarily deciding that the 1 ml. samples were to be extracted with the tip of the pipette 2 cm. from the bottom of the tubes, R_2 became 10.10 cm. Since R_1 remains the same, this changed the constant C' to 8.657×10^{-7}, and the centrifuging times to

Time required	Diameter in millimeters
1 min. 31 sec.	1/512
6 min. 1 sec.	1/1024
24 min. 2 sec.	1/2048

An analysis of another fine sediment gave the following results, using the new developments:

Material Finer Than	Weight by Pipette	By Centrifuge
1/512 mm.	2.0266 gm.	1.4265 gm.
1/1024 mm.	1.2836 gm.	.6778 gm.
1/2048 mm.	.76925 gm.	.54636 gm.

Grade	Per Cent by Pipette	By Centrifuge
greater than 1/512 mm.	3.177%	5.031%
1/512–1/1024 mm.	2.295%	2.312%
1/1024–1/2048 mm.	1.630%	.406%

Here a definite correlation is evident. Since some time had lapsed between the pipette and centrifuge analysis of this particular sediment, it was believed that the smaller results obtained by the centrifuge were due to partial coagulation of the suspension. Consequently, an electric drink mixer, one of the most effective agents of physical dispersion, was used to re-disperse this same suspension. A reanalysis gave the following results:

Material Finer Than	Weight by Pipette	By Centrifuge
1/512 mm.	2.0266 gm.	2.3692 gm.
1/1024 mm.	1.2836 gm.	1.3694 gm.
1/2048 mm.	.76925 gm.	.87498 gm.

This is a rather close check and may be accepted as evidence that the centrifuge method as developed shows promise of accuracy.

Several other fine sediments were analysed in this manner but no closer checks were noted than the one given above. Perhaps the error due to the time involved in bringing the centrifuge to full speed hinders too close a check. That is to say, it was observed that it requires 40 seconds for the machine to reach its full rotational speed. Since the equation used assumes a constant speed of 1670 revs. per minute for the entire time in which particles in the centrifuge tubes are traveling from R_1 (the meniscus) to R_2, an error enters due to the changing speed at the start of each interval of spinning. The time required for all particles larger than 1/512 mm. in diameter to settle below R_2 was stated on page 25 to be 1 min. 31 sec. Since 40 seconds of this time is involved in allowing the centrifuge to reach full speed, for this size at least a deviation is to be expected. For the other longer intervals of time the 40 seconds can be considered as inconsequential.

The centrifuge tubes are small and hold only 5 ml. This means that the particles in suspension in the tubes are going to be subject to a rather strong surface tension between the water and the sides of the glass tubes. This undoubtedly affects the progress outward of the particles being centrifuged. In the pipette method of Krumbein and Pettijohn this difficulty can be disregarded since the sediment grains are settling under gravity in a much wider container than a centrifuge tube, a 1000 ml. graduate. How to correct for this error in the centrifuge method outlined here is unknown at present.

Another source of variation in the centrifuge results is probably due to the rotating or roily motion imparted to the particles at the start and finish of a certain time of centrifuging. However, according to Svedburg, this error is small and may be neglected.

The errors mentioned may prevent an exact check between the pipette method

and the "pipette-centrifuge" method, but it is the conviction of the writer that further experimentation and refinement of the present procedure will result in even a closer check than the one last listed. At any rate, on the strength of the evidence presented, the statement may be made that the "pipette-centrifuge" method may be used with reasonable accuracy for the analysis of the grades below 1/512 mm. of a sediment that has its majority of grains in the larger grades such as the $\frac{1}{16}$–$\frac{1}{4}$ mm. or the $\frac{1}{32}$–$\frac{1}{16}$ mm. grade.

Accordingly, the following procedure is proposed for the size analysis of such sediments:

1. Dry and weigh a representative portion of the sediment. About 30 grams will do.
2. Screen the weighed sample and weigh the portions retained on each sieve. Calculate the per cent in each grade.
3. Place the portion smaller than $\frac{1}{16}$ mm. (.061 mm.) in diameter in a 1000 ml. graduate and add about 1 gm. of sodium oxalate. Fill to the 1000 ml. mark, shake thoroughly, and allow to stand over night. If no flocculation is observable the next morning,
4. Then analyse the suspension down to material less than 1/256 mm. in diameter by the pipette method of Krumbein and Pettijohn.
5. Shake the suspension thoroughly, and at the end of 3 minutes extract a 20 ml. sample from a depth of 10 cm. Divide this among the four 5 ml. centrifuge tubes and spin for 1 min. 31 sec. Brake with the hands at the exact time, and extract with a 1 ml. pipette a sample from each of the four tubes. Evaporate it to dryness. Allow for the amount of sodium oxalate that would be present, and multiply the weight of the dried 4 ml. sample by 250 in order to determine the net weight of material in the whole suspension that is finer than 1/512 mm. in diameter. Subtract this from the quantity of material finer than 1/256 mm. in the whole suspension, as determined by the pipette method. This of course gives the amount in the 1/256–1/512 mm. grade.
6. Discard the contents of each centrifuge tube, rinse, and dry with acetone. Make another 20 ml. extraction from the main suspension as before, and refill the centrifuge tubes with this. Spin this time for the material finer than 1/1024 mm. Follow the same procedure as in 5.
7. Do the same for material less than 1/2048 mm. in diameter.

A study of the method outlined above and the mathematics developed earlier in the paper shows that it is essentially merely an adaptation of the pipette method of size analysis of Krumbein and Pettijohn. The only change is the substitution of centrifugal force for gravity and a modification of Stokes' law to fit the substitution. That this change was justified may be noted by again observing the time schedules on page 23 and page 25. It takes 65 hours and 25 minutes for the settling time of material finer than 1/2048 mm. in diameter in the pipette method, whereas it takes only 24 minutes and 2 seconds for the same thing to be accomplished in the centrifuge method. The time saving is immense.

It is evident that, by following the method outlined in steps 1 through 7, a sediment containing material in the finer grades may be completely analysed in one day. This is true because the longest gravity settling time required is 2 hours 3 minutes. A complete analysis by the ordinary pipette method in one day is impossible.

It is of course necessary to be more exact and to use more careful technique in the centrifuge method because smaller quantities of material are being handled. A balance weighing to the nearest tenth of a milligram is necessary and the extraction from the centrifuge tubes with

1 ml. pipette should be made at the exact point R_3. The required skill is soon developed by the investigator, however. It might be mentioned here that the Steele and Bradfield studies treated larger quantities of material. An International centrifuge was used with eight 100 ml. tubes. Each tube was filled with 25 ml. of suspension. 5 ml. samples were extracted at a depth of 2 cm. In the method outlined in this paper, the samples are extracted at a depth of 6.25 cm., thus allowing a longer distance for particles with equal settling velocities to group together. A closer approximation to the conditions of the mathematical theory is thus obtained.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 28–34,
FIGS. 1–2, TABLES 1–2, APRIL, 1943

SPHERICITY DETERMINATIONS OF PEBBLES AND SAND GRAINS

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ABSTRACT

The sphericity of pebbles and sand grains is simply and rapidly determined by taking ratios of the diameters of the particles. It is proved that for ellipsoidal and spherical shaped grains this method yields results identical to those of Wadell. A comparison of the two methods for a number of sand grains and pebbles shows that they yield essentially the same values even for non-ellipsoidal or non-spherical shaped particles.

INTRODUCTION

During a recent study of the Bethel sandstone of south central Illinois by the writers, the question arose of developing short cuts in sedimentational procedures which would yield results comparable in accuracy to those derived by using the standard procedures and yet which would not be as time consuming. Recent work by Krumbein has greatly simplified the work of making roundness determinations, and it is hoped that the methods herein proposed will equally simplify sphericity[1] determinations of both large and small particles.

SPHERICITY DETERMINATIONS OF GRAINS

Fundamentally, the sphericityana lysis of grains is based upon the projection method of Wadell. His method consists of mounting the grains upon a glass slide and projecting them upon a sheet of paper. The ratio of the diameter of the circle having the same area as the area of the projected grain to the diameter of the smallest circumscribing circle gives the sphericity of the grain. This method becomes rather tedious when many determinations must be made, even though the direct outline of the grains are substituted for the traced outlines. Recently Riley simplified the method to a considerable degree. However, it has been found possible further to shorten the method and at the same time to secure results which fall close to those derived by the Wadell projection method except for extreme cases.

The writers determine the sphericity of a grain by using the square root of the ratio of the short and long diameter of the projected image, where the short diameter is defined as the minimum width of the projected image of the grain and will usually correspond with the intermediate diameter of the grain, and the long diameter is the longest measurement of the grain, or its projected image, taken at right angles, or essentially so, to the short diameter. The short and long diameters will rarely be bisectors of each other. For a perfect circle or an ellipse, the sphericity value will be identical with that given by Wadell's projection method. The proof of this follows:

By definition

$$\psi_{wg} = \frac{d_n}{D_c}$$

where ψ_{wg} is the Wadell projection sphericity, d_n is the diameter of a circle whose area is equal to that of the grain, and D_c is the diameter of the smallest circle circumscribing the grain, which in most cases is equal to the long axis of the grain. Therefore, the area of a circle with the

[1] In this paper the term shape is used when the particle is compared to some geometrical form; the term sphericity is confined to a description of the approach to or departure of the particle from a true sphere irrespective of the geometrical shape of the particle.

same area as the grain image (A_i) is given by

$$A_i = \frac{\pi d_n^2}{4}.$$

The area of an ellipse (A_e) is given by

$$A_e = \pi\left(\frac{a}{2}\right)\left(\frac{b}{2}\right)$$

where a and b represent the full length of the major and minor axes. These axes correspond with the long and short diameters of the grains. Equating

$$A_i = A_e = \frac{\pi d_n^2}{4} = \frac{\pi ab}{4}$$

or,

$$d_n = \sqrt{ab}$$

therefore,

$$\psi_{wq} = \frac{d_n}{D_c} = \frac{\sqrt{ab}}{a} = \sqrt{\frac{b}{a}} = \psi_{pq}$$

which is the writers' projection sphericity.

Since most grains approach an elliptical or circular form, the sphericity determination by the two methods will not deviate widely. A comparison of the sphericity of twenty-five grains by the two projection methods is given in Table 1. It will be noted that the two projection methods give almost identical results, especially since for all practical purposes the second decimal point is of little real significance. In general, Wadell's method gives values slightly lower. In the case of triangular or equant shaped grains, the writers' method yields a value considerably higher, but this type of grain normally forms only a small percentage of any sample.

The same inherent difficulty exists in both Wadell's and the writers' projection methods, namely, that the farther a grain departs from an ellipse or circle, the greater the difference between the projection sphericity and the true sphericity of the object.

Table 2 gives a comparison of the projection two-dimensional sphericity with the three-dimensional sphericity determinations. From this table it is evident that the two-dimensional sphericity determinations yield much higher values. This is especially true the more the shape of the particle departs from that of a true sphere. Based upon Zingg's shape classification, two-dimensional sphericity determinations of disc and triaxial shaped grains yield sphericities most in error; rod and spherical shaped grains yield values which are also too high, but which are more nearly comparable to those given by the three-dimensional study.

It is evident from the above study that the two-dimensional sphericity analysis for grains is not altogether satisfactory.

TABLE 1. *Comparison of two-dimensional sphericity measurements of sand grains—Wadell's projection sphericity (ψ_{wq}) and the writers' sphericity (ψ_{pq}).*

ψ_{wq}	ψ_{pq}	$\psi_{pq}-\psi_{wq}$	ψ_{wq}	ψ_{pq}	$\psi_{pq}-\psi_{wq}$
.89	.96	.07	.90	.89	−.01
.75	.75	.00	.88	.93	.05
.82	.80	−.02	.81	.84	.03
.89	.94	.05	.87	.89	.02
.88	.90	.02	.89	.92	.03
.91	.97	.06	.91	.94	.03
.83	.84	.01	.74	.74	.00
.88	.90	.02	.82	.86	.04
.82	.83	.01	.77	.85	.08
.92	.94	.02	.76	.76	.00
.70	.75	.05	.93	.96	.03
.89	.92	.03	.88	.91	.03
.78	.76	−.02			

The writers have been working on a three-dimensional method of securing sphericity determinations of fine grained particles and hope shortly to be able to perfect a method. Fortunately two-dimensional studies are usually confined to the study of the sand grade sizes of sediments. These are usually dominantly made up of quartz or feldspar of which the grains tend to be spherical in shape rather than disc-shaped. However, when sphericity determinations are being made of a sand deposit, it is well to either confine the determinations to one variety of mineral or to keep a record of the mineral species upon which it was made.

TABLE 2. *Comparison of three-dimensional and two-dimensional sphericity measurements of pebbles—Wadell's three-dimensional sphericity (ψ_{wp}), the writers' three-dimensional sphericity (ψ_{pp}), and the writers' two-dimensional sphericity (ψ_{pq}).*

Pebble diameters (mm)			Three-dimensional Sphericity			Two-dimensional Sphericity		Zingg Shape
a	*b*	*c*	ψ_{wp}	ψ_{pp}	$\psi_{wp}-\psi_{pp}$	ψ_{pq}	$\psi_{wp}-\psi_{pq}$	
51	39	11	.58	.55	.03	.87	−.29	Disc
18	15	10	.73	.77	−.04	.90	−.17	Sphere
34	31	16	.71	.75	−.04	.96	−.25	Disc
58	38	28	.70	.67	.03	.82	−.12	Rod
60	37	33	.67	.69	−.02	.78	−.11	Rod
27	17	13	.64	.67	−.03	.79	−.15	Rod
13	13	10	.92	.93	−.01	1.00	−.08	Sphere
32	21	16	.64	.68	−.04	.81	−.17	Rod
21	18	13	.82	.81	.01	.93	−.11	Sphere
30	21	14	.68	.68	.00	.83	−.15	Sphere
37	27	17	.65	.68	−.03	.85	−.20	Disc
38	28	15	.65	.66	−.01	.86	−.21	Disc
40	25	22	.64	.69	−.05	.79	−.15	Rod
30	23	12	.63	.67	−.04	.87	−.24	Disc
22	21	18	.87	.92	−.05	.97	−.10	Sphere
21	18	16	.86	.87	−.01	.93	−.07	Sphere
20	18	12	.85	.82	.03	.95	−.10	Sphere
22	19	15	.83	.84	−.01	.93	−.10	Sphere
17	17	12	.87	.90	−.03	1.00	−.13	Sphere
22	19	18	.84	.90	−.06	.93	−.09	Sphere
25	21	1.6	.38	.38	.00	.92	−.54	Disc
19	18	13	.84	.87	−.03	.97	−.13	Sphere
28	15	6	.49	.49	.00	.73	−.24	Triaxial
34	31	27	.83	.90	−.07	.96	−.13	Sphere
26	18	15	.70	.74	−.04	.83	−.13	Sphere

PROJECTION ANALYSIS TECHNIQUE

To make an analysis of the sphericity of a sand sample, the grains are first cleaned, if necessary, and then mounted on a glass slide. For most sands, the best mounting medium is a mixture of two-thirds water and one-third glycerin. The glycerin retards evaporation of the water so that the slide will remain intact for several hours and the water lowers the index of refraction of the glycerin so that sharp and distinct outlines of the grains result. Furthermore, this mounting medium is cheap, easily secured, and the slides can readily be cleaned. The slide is then placed on a projector[1] so that the image of the grains is thrown vertically downwards upon a table top. The short and long diameters of the grain are readily measured directly from the projected

[1] A very satisfactory device for this purpose is the "Promar Microscopic drawing and projection apparatus" offered by the Clay-Adams Co., New York, N. Y.

grain image by means of a millimeter scale.

After the grains have been measured, the sphericity is calculated by using figure 1. This chart is prepared by plotting the square root of the short diameter (b) against the square root of the long diameter (a) of the grains and then drawing in the boundary lines between the sphericity classes. The sphericity is given by locating the intersection of the vertical line corresponding to the a diameter with the horizontal line corresponding to the b diameter.

SPHERICITY DETERMINATIONS OF PEBBLES

True sphericity has been defined by Wadell as the ratio of the surface area of a sphere of the same volume as the particle to the actual surface area of the particle. To facilitate computations, a practical formula for determining the sphericity of pebbles was developed by him. In this formula the volume of the pebble is determined and from it the diameter of the sphere having the same volume as the pebble is calculated. The ratio of this calculated diameter to the diameter of the smallest circumscribing sphere (usually the longest axis of the pebble) yields the sphericity of the pebble.

The writers' proposed sphericity method simply involves the taking of the cube root of the ratio of the product of the two short pebble diameters to the square of the long diameter of the pebble. In the preceding section on projection sphericity determination, it was pointed out that the long diameter of the grain image corresponds to the long diameter of the grain, and the short diameter of the image to the intermediate diameter of the pebble. The c-diameter, or shortest diameter of the pebble, is the diameter at right angles to the other two. None of these three diameters need intersect, and rarely are they bisectors of each other.

The diameters of a pebble can be readily determined by laying it down on a table in its most stable position. In this position, the b-diameter, or intermediate diameter, will be the shorter diameter of the pebble outline as one looks down on the top of the pebble; the a-diameter will be the longer dimension of the pebble as seen from above. This will usually be essentially at right angles to the b-diameter; the c-diameter will be the shortest

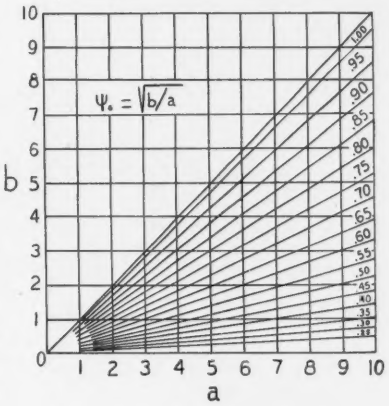

FIG. 1. Chart for determination of sphericity of grains.

dimension and will be essentially perpendicular to the table top. To select these last two diameters, it may be simplest to hold the pebble between the thumb and finger at the ends of the b-diameter and rotate the pebble about this axis. The longest diameter perpendicular to the b-diameter is then the a-diameter and the c-diameter will be found by rotating the pebble about the b-axis another ninety degrees.

For the case of an ellipsoidal or spherical pebble, the sphericity given by Wadell's method and the writers' method are identical. As the pebble departs from these shapes the values differ, the writers' values in most cases being a little higher. The proof of the identity of these two sphericity measures follows for the case of an ellipsoid.

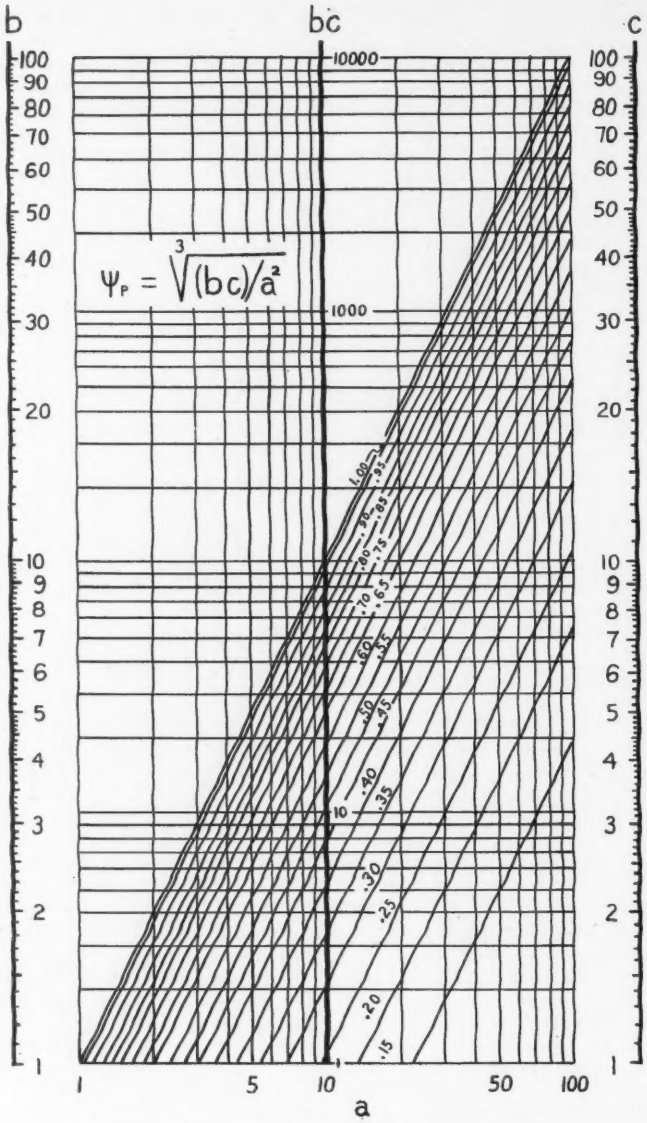

FIG. 2. Chart for determination of sphericity of pebbles.

By definition

$$\psi_{wp} = \frac{d_{ns}}{D_s}$$

where ψ_{wp} is Wadell's sphericity for a pebble, d_{ns} is the calculated nominal diameter of the pebble, or the diameter of the sphere whose volume is the same as that of the pebble, and D_s is the diameter of the smallest circumscribing sphere which is in almost all cases identical to the a-diameter of the pebble.

The volume of a sphere (V_s) of the same volume as the pebble is given by

$$V_s = \frac{4}{3}\pi\left(\frac{d_{ns}}{2}\right)^3$$

and the volume of an ellipsoid (V_e) is given by

$$V_e = \frac{4}{3}\pi\left(\frac{a}{2}\right)\left(\frac{b}{2}\right)\left(\frac{c}{2}\right)$$

where a, b, and c are the full lengths of the axes of the ellipsoid; equating,

$$V_s = V_e = \frac{4}{3}\pi\left(\frac{d_{ns}}{2}\right)^3 = \frac{4}{3}\pi\left(\frac{a}{2}\right)\left(\frac{b}{2}\right)\left(\frac{c}{2}\right)$$

or

$$d_{ns} = \sqrt[3]{abc}.$$

Therefore,

$$\psi_{wp} = \frac{d_{ns}}{D_s} = \frac{\sqrt[3]{abc}}{a} = \sqrt[3]{\frac{bc}{a^2}} = \psi_{pp}$$

where ψ_{pp} is the writers' pebble sphericity.

Table 2 gives a comparison of Wadell's (ψ_{wp}) and the writers' (ψ_{pp}) sphericity for twenty-five pebbles. Out of several hundred determinations covering a wide range of shapes and degrees of sphericity, no difference between the two methods of over 0.10 was found and most of the differences were in the neighborhood of 0.04. When those pebbles that showed a wide variation between the two methods were examined, it was found that they were frequently deeply pitted or were otherwise abnormally irregular so that the resulting ψ_{wp} based either upon weight or volume would be much lower than would normally be expected.

Wadell notes that his practical formula gives sphericities which on the average are 0.1 lower than the sphericities yielded using the ratio of the surface area of a sphere of the same volume as the particle to the actual surface area of the particle, which ratio is the true sphericity of the particle. It will be noted from Table 2 that in almost all cases the writers' sphericity is larger than Wadell's and therefore approaches the true sphericity of the pebble to a greater degree.

PEBBLE ANALYSIS TECHNIQUE

After the three diameters of the pebble have been determined, their lengths are readily measured with a pair of calipers or a sliding block mounted on a ruler. To simplify calculations a chart has been prepared and is shown in figure 2. In determining the sphericity of a pebble the dimensions of the b and c diameters are located on the vertical b and c scales and connected by a transparent straight-edge. The point at which the straight-edge crosses the vertical bc-scale yields their product. The intersection of the horizontal line from the point which represents the product of the b and c diameters of the pebbles with the vertical line from the a-scale, which corresponds to the a-diameter, locates the point which gives the sphericity of the pebble along the diagonal lines of the chart. For example, using a pebble with the diameters $a = 24$, $b = 20$, and $c = 10$ mm., the line joining the points $b = 20$ and $c = 10$ on the b and c scales respectively, intersect the vertical bc line at 200. The horizontal line from this point which intersects the vertical line from $a = 24$ on the a-scale indicates a sphericity of 0.70 for the pebble.

SUMMARY

1. The sphericity of a grain is given by the ratio of the square root of the short diameter of the outline of the grain to the long diameter of the grain.

2. The sphericity of a pebble is given by the cube root of the ratio of the product of the intermediate and short diameters of the pebble to the square of the long diameter.

3. There is a great need of a method of securing a truer measure of the sphericity of grains. This method will probably have to depend upon a three-dimensional analysis.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 35–39, FIGS. 1–3, APRIL, 1943

EFFECT OF CHANGE OF WAVE SIZE ON THE SIZE AND SHAPE OF RIPPLE MARKS[1]

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ABSTRACT

Although ripple marks are somewhat resistant to the effect of changes in the size of the generating waves, yet when waves decrease in size there also usually occurs a change in the size and shape of the underlying ripples. Some new forms of ripples are described. One of these has rounded crests and angular troughs and is the reverse of the common symmetrical wave formed ripple. Another type consists of a series of alternately wide and narrow ripple marks. Both forms occur in relatively narrow belts near shore. Conditions are indicated under which fossil ripple marks can be used as a help in determining sequence in sedimentary beds.

A perusal of the literature of ripple marks indicates that the earlier studies were directed largely toward discovering their nature and trying to determine the laws governing their formation. Some experimental work was attempted which was supplemented by mathematical calculations and by observation of ripples in running water and on the bottom of quiet bodies of water. Following these studies and observations attempts were made to interpret conditions under which certain sedimentary rocks had been formed from evidence from fossil ripples preserved in them. Evidently the truth of such interpretations depends on the accuracy of observations of recent ripple marks and the truth of the laws deduced regarding them.

Almost without exception the observations of wave formed ripple marks have been confined to those found on the bottom of quiet water bodies under the supposition that such ripples are the same ones that were formed during the previous periods of wave action. This assumption receives its main support from two of Forel's conclusions. He says, as translated by Johnson (1919), "Ripples once formed do not experience a change in spacing as a result of diminishing amplitude of the water, although the original spacing does depend on the amplitude of oscillation of the water, as pointed out by de Condolle." And again, "In a given locality, ripple marks almost always form with the same spacing, regardless of the varying intensity of winds and waves affecting the water body." This is not in accordance with my observations and leads me to suspect that either Forel's field observations were not very extensive or that he was somewhat unfortunate in the time and place in which he did his work. The latter might easily happen for although ripple marks which have once formed have considerable stability yet a change in intensity or direction of the waves lasting for several hours will cause either an entirely new set of ripples to form or produce a change in the shape of those already formed. Often a shift of direction of the wind up to 30 or 40 degrees will bring no change in ripple form for some time unless accompanied by an increase in wave size. This allows an actual variation in direction of wind of 60 to 80 degrees without causing an appreciable variation in the ripple form. However if the wind remains in the new quarter for a considerable time or for a short time with an increased velocity, cross ripples will form

[1] With the support of a grant from the American Philosophical Society.

and finally an entirely new set will be present.

Sometimes ripples formed by large waves persist for a long time when the succeeding waves are rather suddenly decreased in size. This is because for each size of sediment there is a limiting depth below which the movement caused by the waves is not of sufficient intensity to cause the formation of new ripple marks although it may cause a very gentle movement of the sediment. This limiting depth can often be observed along the sandy shores of small lakes which deepen rapidly close to shore. Ripples formed here by waves of a constant size will normally become smaller with depth and then die out (Evans, 1942). The depth of the water where they disappear is the limiting depth for that particular size of waves and sediment.

Some of the most interesting changes in ripple marks occur as the result of a gradual decrease in wave size. Such changes agree perfectly with the mathematical theory of wave motion since wave formed ripple marks are caused by the oscillatory movements set up on the bottom by the passing waves and such movements decrease rapidly with depth. Thus, it is a mistake to assume that the ripples seen on the bottom of a water body during calm weather are necessarily the same, either in size or shape, as those which were produced by the preceding strong winds. They are much more likely to be the result of changes produced in the original ripples by the decreasing waves after the storm. Such changes take numerous forms, but they can usually be explained if it is kept clearly in mind that ripples once formed are somewhat resistant to change and that for any given depth the oscillatory movement decreases with increase in depth of water or decrease in size of wave (Evans, 1942).

One change that often occurs near shore and is likely to be quite unsuspected is a change from asymmetrical oscillation ripples (Evans, 1941) to symmetrical oscillation ripples as the waves decrease in size. I have often observed this to happen a short distance out from shore in Lake Michigan with water around two feet deep. During the last week of August, 1940, the east shore of Lake Michigan in the vicinity of White Lake was subjected to several days of steady wind which caused waves around four feet high. This caused breakers out some distance and the formation of a belt of asymmetrical ripples extending out 100 feet or more from the shoreline. At the close of this period the wind continued to hold in the same quarter and to die down very gradually until there was a calm which continued for several days. As a result the asymmetrical ripples were nearly all changed to the symmetrical form. The only asymmetrical ripples remaining were those on the top of an offshore subaqueous ridge on which gentle breakers had continued to act until the wind had practically ceased. This tendency to change asymmetrical to symmetrical ripples as the wind goes down may largely explain the failure of most investigators to observe their presence. Mrs. Hertha Ayrton seems to be the only recorded exception (1910). It is difficult to understand how Kindle (1917) could have failed to observe the presence of asymmetrical ripples in Lake Erie unless we assume that his observations were conducted only during calm weather. He goes so far as to state that the presence of asymmetrical ripple marks in rock can be taken as evidence that the sediments were laid down under marine conditions. Yet asymmetrical ripple marks are nearly always present on a sandy bottom even though the breakers are only a few inches high.

An interesting form of ripple which has never before been described is sometimes produced not far from shore as the waves decrease in size after a storm. It has a rounded crest and an angular trough (figs. *1(a)* and *2*). The geological importance of the discovery of this form is owing mostly to Kindle's statement (1917, p. 55) that "Since no examples of ripple

marks with rounded crests and angular troughs are known, the angular parts of the profile can be considered to represent the crests when found in beds whose order of superposition is not known." A statement to this effect is also made by Bucher (1919, pp. 183–184). According to my observations this type of ripple mark is confined to a relatively narrow belt not far from shore. It forms as the result of a rapid decrease in wave size and usually has a short life. Therefore the finding of fossil ripple marks of this form may be considered as an evidence of overturning although it is not a proof.

I have not been able to analyze exactly the method of its formation, but in the succeeding calm period it is always found in the same place as that occupied by some of the asymmetrical ripples during the preceding blow and is formed during the period of decreasing wave size as the wind decreases in velocity. It appears to be a result of the decreasing and more uniform reciprocating movements which occur as the place of the breakers is taken by the smaller oscillation waves. If it were not for the presence of the asymmetrical ripple marks, symmetrical ripple marks of a lesser width would probably form. The action may be aided by the gentle hydraulic currents that move out from shore due to the falling water level on a lee shore as the velocity of the onshore wind decreases. The result is an over-filling of the former troughs with the new angular troughs slightly shoreward of the old crests.

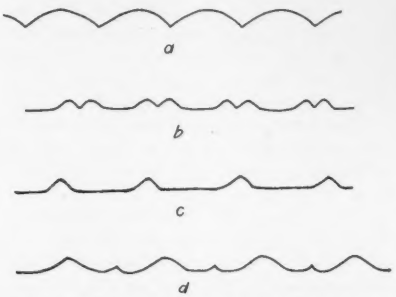

FIG. 1. Cross sections of ripple mark forms.

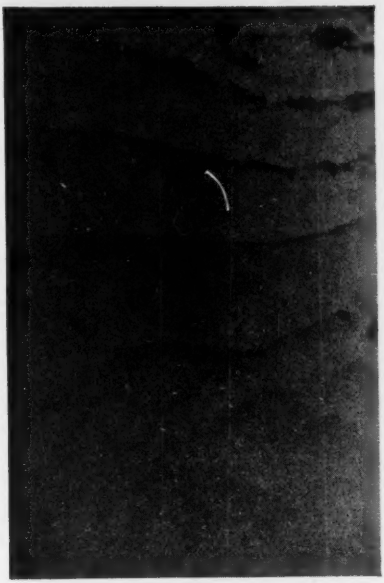

FIG. 2. Ripple marks with rounded crests and angular troughs, Silver Lake.

Another newly discovered form of ripple marks that occasionally appear after a blow is shown in figs. *1(b)* and *3*. These consist of a series of alternately wide and narrow ripples. They are produced when the waves are slowly decreasing in size. They are found on gently sloping bottoms and occur in relatively narrow belts parallel to the shoreline. Sometimes I have found two or more of these belts on a gently sloping terrace with wide belts of ripples of uniform width between them. Their formation probably requires a rather delicate adjustment of wave size to water depth. They form when the surges caused by the passing waves are stronger in one direction than in the other. The effect is to first sharpen the crest of an already formed ripple and

then to cause a line of sand like a small windrow to move from the crest down the side of the ripple in the direction of movement of the water. If the return surge is not strong enough to carry the small sand ridge thus formed back to the crest it is reinforced as each succeeding wave passes and soon a secondary ridge is built near the first thus giving the appearance of alternate wide and narrow ripples. It forms best with a gentle dead swell coming in

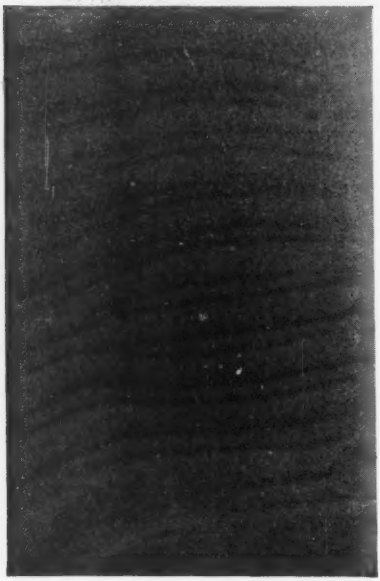

FIG. 3. Alternately wide and narrow ripple marks, bottom of Silver Lake after storm.

parallel to the original ripples. If found inverted, this form is certain proof of overturning.

A very common change of ripple mark form that occurs with decreasing wave size is the flattening of the rounded bottoms of symmetrical ripples to such an extent that the crests change from an arcuate to a triangular cross-section. This is caused by the shorter alternating movement of the water on the bottom which accompanies the smaller waves. The effect of the reduced movement is to sharpen the crests of the ripples and flatten their troughs (fig. *1*(*c*)). Sometimes a secondary crest forms in the flat bottom as shown in figure *1*(*d*). This is probably the result of the reciprocating movement on the bottom being about half that which formed the original ripples. This form was described by Van Hise and has since been frequently mentioned as giving positive evidence of overturning of beds if found in the inverted position.

When a heavy sea is followed by a long period of gentle wave movement a rounding and smoothing of the ripples occur along with some displacement along the longitudinal axis. The effect is to produce an irregular and disintegrated appearance of the ripple marks which is easily recognized. This is because the gentler movements caused by the smaller waves are sufficient to cause some movement but not enough to result in a new ripple system. The change is brought about very gradually and is long continued.

Another surprising phenomenon which sometimes occurs when a strong sea is followed rather quickly by a calm is the absence of ripple marks. The processes which produce this smoothing of the bottom have never been completely observed but it perhaps results from the irregularities of movement on the bottom produced by the rapidly decreasing sea combined with a rapid deposition of sediment from suspension. I have seen this happen on the east side of Lake Michigan when a quick violent storm was followed within a short time by a dead calm.

The occurrence of numerous changes in ripple mark form that take place when waves are decreasing in size suggests that changes may also occur during times of increasing wave size. However such changes are difficult to observe and are of little importance to the geologist in sediment study since they are preserved for only a short time. On the other hand the forms produced during the time of decreasing wave action often continue in

existence for a considerable time because the decreasing wave action allows them to fall out of the zone of wave disturbance where they remain with comparatively little change until the recurrence of large waves.

CONCLUSIONS

1. Although wave formed ripple marks are stable within certain limits of wave action yet they are often changed in both size and form by continued action of waves of decreasing size.

2. Ripple marks seen at time of still water are usually secondary forms produced by changes in the original ripples by the smaller succeeding waves.

3. Ripple marks having rounded troughs and sharp crests when found inverted are an indication but not a proof of overturning since ripple marks having rounded crests and angular troughs occur occasionally in limited areas.

4. Ripple marks having sharp triangular ridges with flat troughs between or with the troughs containing a small secondary ridge are certain proof of overturning if found inverted.

5. The alternately wide and narrow series of ripple marks, if found inverted, are certain proof of overturning but will be rarely found as this form is of limited extent.

6. The absence of ripple marks in sandy sediments may be an indication of relatively deep water at the time of deposition but does not prove it as shallow sediments are sometimes found to be swept smooth after a storm.

7. Symmetrical oscillation ripples with smoothed and rounded slopes and having a very irregular longitudinal axis indicate that after their formation they lay for a considerable time just below the sphere of effective wave action.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 1, PP. 40–42,
FIG. 1, TABLE 1, APRIL, 1943

SEDIMENTATION NEAR JUNCTION OF MAQUOKETA AND MISSISSIPPI RIVERS

DISCUSSION

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The problem of determining the amount of sediment delivered by tributaries to main stream deposits has interested me for some years. Consequently, Mr. Swenson's article entitled "Sedimentation near Junction of Maquoketa and Mississippi Rivers" (this journal, vol. 12, pp. 3–9, 1941) was read with unusual care.

On the basis of textural differences, Mr. Swenson concluded that 30 per cent of the sediment deposited in the Mississippi River channel in the 4½ mile reach below the mouth of the Maquoketa River had been derived from the Maquoketa. Briefly summarized Mr. Swenson's pertinent data are as follows:—(1) In 1932 the lower 7.5 miles of the Maquoketa River were straightened with cut-off channels that had a 12-foot bottom width; (2) by 1937 this channel had widened by erosion to 150 to 250 feet; (3) sedimentation in the Mississippi River below the mouth of the Maquoketa River increased, and from 1933 to 1937 inclusive, a total of 911,000 yards of sediment was removed by dredging; (4) the average texture of the eroded material was approximated by sampling the present banks of the ditch (table 1); (5) the average texture of the Mississippi

TABLE 1

Size grade *mm.*	*a* %	*b* %	*c* %	*d* %	*e*	*f* %	*g*	*h* %
16–8	.3		.1	.2	1.0	.2	1.0	.2
8–4	1.8		.7	1.2	1.0	1.0	1.0	1.0
4–2	4.0	.2	1.6	2.9	1.0	2.6	1.0	2.4
2–1	7.9	.4	4.9	5.6	1.0	5.1	1.0	4.8
1–½	29.6	2.7	20.4	21.2	1.0	20.0	1.0	19.5
½–¼	49.7	11.3	39.9	38.2	1.0	37.8	.9	37.3
¼–1/8	5.8	11.9	6.6	7.7	.8	8.8	.5	9.1
1/8–1/16	.7	6.8	3.0	2.6	.6	2.8	.4	3.4
1/16–1/32		23.7	9.7	7.2	.6	8.8	.3	9.0
1/32–1/64		24.6	7.6	7.4	.5	6.2	.2	7.8
1/64–1/128		9.2	3.1	2.8	.5	2.9	.2	2.9
1/128–1/256		4.9	1.3	1.5	.4	1.2	.2	1.2
<1/256		4.3	1.1	1.3	.4	1.1	.2	1.1

Average size grade distribution of sediment from,
a—Mississippi River above mouth of Maquoketa,
b—Maquoketa River banks,
c—Mississippi River below the mouth of the Maquoketa,
d—Computed sample with 30% from Maquoketa and 70% from the Mississippi River.
f—Computed sample with 50% from Maquoketa and 50% from the Mississippi, using the differential rates of transportation in column *e*.
h—Computed sample with 70% from Maquoketa and 30% from the Mississippi, using the differential rates of transportation in column *g*.

River bed above and below the mouth of the Maquoketa was approximated from bottom samples (table 1).

Mr. Swenson found by calculation that a mixture of 30 per cent of Maquoketa sediment and 70 per cent of Mississippi sediment had about the same texture as the sediment in the Mississippi River channel below the mouth of the Maquoketa. He concluded that about 30 per cent of the sediment actually did come from the Maquoketa.

Basic to this conclusion is the validity of Mr. Swenson's unstated, but fundamental assumption, namely, that in the 4½ mile reach of the Mississippi River each size of sediment must have been deposited in essentially the same proportion in which it was contributed from the Maquoketa and the Mississippi. Debris from the Maquoketa is composed of about one-third sand and two-thirds silt and clay. Mr. Swenson thus assumes that sand, which commonly moves along stream beds by traction and saltation, will be carried downstream and deposited at the same average rate as will silt and clay that is transported largely in suspension. He also assumes that there will be equal opportunity for deposition of the silt and clay from the Maquoketa River and the coarse sand and gravel brought down the Mississippi River. In lakes, reservoirs, and other bodies of quiet water such deposition of all sizes may occur, although even in these places there is a tendency for the coarser sediment to be concentrated in deltas. For rivers, I know of no published data that would confirm Mr. Swenson's assumption.

Omitting consideration of the suspended load, the validity of the assumption for sand alone is also questionable. In the Enoree River near Taylors, South Carolina, measurements of the texture of the bed-load and of the bed deposits for a mile above the Soil Conservation Service Hydraulic Installation indicate that the sand in the stream load is much finer than the sand in the bed deposits (Einstein, Anderson, and Johnson, 1940). During the flood of August, 1939, for example, the median size of the sediment .175 mm. or larger carried past the station was 0.27 millimeters, whereas, the median size of the bed deposits was 0.78 millimeters. The distribution by sizes is shown in figure 1. Because this 1939 flood was one of the highest during the 5-year period of record, and because other measurements show that the stream load of

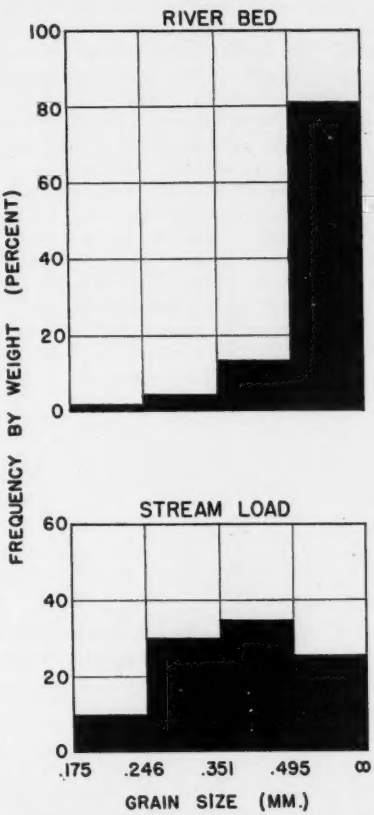

FIG. 1.—Histograms of bed and suspended loads of Enoree River, South Carolina, in the flood of August, 1939.

the Enoree River coarsens with increasing stage, the texture of the stream load would probably be even finer for an extended period of low, medium, and high stages, and the difference between stream load and bed textures even greater.

Flume experiments provide additional information. Straub (1935) has reported that " . . . in this case (contrary to the usual conception) the coarser material was transported more rapidly than the finer, the latter being predominantly present near the headwater-end of the flume. . . . Similar occurrences have been observed with material of finer mechanical composition. Depending apparently upon the flow-conditions and the type of material, segregation upon deposition may take place either from fine to coarse (from one end of the channel to the other) or the reverse." Chang (1940) has also reported that coarser particles move in greater quantities than the finer.

I do not think that the data now available from flume studies or measurements on rivers indicate that differential rates of movement occur in all rivers or even in most rivers. In fact, it seems probable that when sands are being moved downstream in ripples or sand waves all sizes of grains move at the same average rate. I should like to point out, however, that if particles of different sizes were transported at differential rates in Mr. Swenson's study area, the contribution from the Maquoketa River may have been more or less than 30 per cent. By assuming the differential rates shown in table 1, for example, Maquoketa contributions of 50 per cent and 70 per cent may be computed.

Until more is known concerning the differential rates of sediment transportation, the use of textural differences alone to measure tributary contribution to main stream deposits will be subject to serious question.

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THE GULF OIL CORPORATION FELLOWSHIP IN GEOLOGY IN THE UNIVERSITY OF CHICAGO

Announcement is made of the establishment by the Gulf Oil Corporation of a Fellowship in Geology at the University of Chicago. First award of this Fellowship will be made for the school year 1943–44 provided qualified candidates are available under war conditions.

The Fellowship stipend will approximate $1200 a year, the Gulf Corporation contributing $900 and the University making available additional funds or allowances equivalent to the tuition requirements, normally $300.

The initial award will be in the field of Sedimentation and candidates must have had the equivalent of at least a year of graduate work in geology at an institution of recognized standing. The Fellowship holder will be expected to devote part of his time to research in sedimentation. The Fellowship may be renewed on recommendation of the Department. Renewal at the end of nine months, rather than at the end of a twelve-month period, is possible if the Fellow works under an accelerated program.

Application forms may be obtained from the Department of Geology, University of Chicago, and must be returned to the University before March 1. The award will be announced April 1.

REVIEW

Physics of the Earth—IX Hydrology, by O. E. MEINZER and Collaborators, pp. i–xi, 1–712, McGraw-Hill Book Company, New York (1942).

Hydrology, the science which treats of water, is truly a middle-ground science for just as water plays an important and frequently a major role in geology, physics, chemistry, meteorology, biology and the other sciences, to a somewhat similar degree these sciences play important roles in the science of hydrology. In order to give more attention to research in these middle-ground sciences, a large committee of the National Research Council undertook to prepare a series of volumes on the Physics of the Earth. The volume on hydrology is the latest of the series.

The work under review was prepared by a committee of twenty-four hydrologists and geologists under the general editorship of Doctor O. E. Meinzer, of the Division of Ground Water of the United States Geological Survey. Because of the dual interests and qualifications of the writers of the book, it is of particular interest to both hydrologists and geologists.

Following an Introduction by Doctor Meinzer, there follows in order chapters on Precipitation by Merrill Bernard; Evaporation from Free Water Surfaces by Sidney T. Harding; Snow and Snow Surveying; Ice by James E. Church; Glaciers by Francois E. Matthes; Lakes by Sidney T. Harding; Infiltration by LeRoy K. Sherman and George W. Musgrave; Transpiration and Total Evaporation by Charles H. Lee; different topics of Soil Moisture by Karl v. Terzaghi and Leonard D. Baver; Ground Water by O. E. Meinzer and Leland K. Wenzel; nine aspects of Runoff by Adolph F. Meyer, Charles H. Pierce, Royal W. Davenport, William G. Hoyt, LeRoy K. Sherman, Clarence S. Harvis, and Walter B. Langbein; Droughts by William G. Hoyt; Physical Changes Produced by the Water in the Earth by W. H. Twenhofel, Harry R. Leach, Lorenz G. Straub, Charles S. Howard, and Margaret D. Fostor; Hydrology of Limestone Terranes by Allyn C. Swinnerton; and Hydrology of Lava-Rock Terranes by Harold T. Stearns. The index covers eight pages and seems to be comprehensive.

The frontispiece of the volume illustrates the hydrologic cycle, or the circulation of the water from the sea, through the atmosphere to the land, and thence back to the sea, with many delays and short circuits in all parts of the cycle. The cycle has glaciers, lakes, soil moisture, ground water, runoff, erosion, and transportation of both organic and inorganic matter as bi-products. These form a part of the field of geology. Essentially every phase of the cycle and the bi-products is considered by a competent authority in a chapter or a section of a chapter. The work is well documented with over 950 references and, in addition, reference is made to bibliographies of the subjects considered.

The Introduction by Meinzer emphasizes that the science of hydrology involves measurement of the quantities and rates of movement of water at all times and in every stage of the cycle. Particularly noteworthy is the excellent treatment of the historical development of the science. Geologists will be particularly interested to read the dialogue between "Theory" and "Practice" written by Bernard Palissy, pioneer paleontologist, and to have recalled that some of the earliest geologic sections ever drawn were used to illustrate the source and mechanism of artesian water. Engineers will be interested to know that it was due to an extensive study of lakes, canals and rivers that DeWitt Clinton became so convinced of the feasibility of the Erie Canal that he promoted it with such vigor that when elected governor of the State of New York, he had the public support of the construction assured.

Particularly excellent chapters are difficult to select as all are considered good.

The one on Snow and Snow Surveying; Ice by Church will appeal to many as it considers such topics as altitude of maximum snowfall, density of snow cover, methods of measurement, forecasting, stream flow from snow surveys, conservation of snow, the melting of snow, avalanches and evolution of ice in streams. The chapter on glaciers by Matthes brings this subject to date by a recognized authority in the field. Unpublished theories of glacier flow are presented as well as recent variations of glaciers viewed in relation to the Pleistocene ice age.

Newly developed techniques on infiltration, relation of time to amount of infiltration, and other topics are considered by Sherman and Musgrave. The subject of transpiration, presented by Lee, presents much experimental data on transpiration and the consumptive use and discharge of water by plants.

Ground water is discussed by Meinzer and Wenzel from the points of view of discarded theories to such practices as ground water recharge which relatively recently has become popular. Reports of recent pumping tests are given. Runoff is separated into divisions of: methods of stream gaging, long records of river flow, the runoff cycle, the unit hydrograph method, prediction of runoff, floods, storage in relation to flood waves, and artificial storage. Each topic was prepared by an authority in the field.

The chapter on Physical Changes produced by the Water of the Earth includes sections on erosion, mechanics of rivers, transportation of mineral matter by surface waters, and chemistry of ground water. This chapter should have interest to geologists as well as hydrologists.

The final chapters on the Hydrology of Limestone and Volcanic Terranes present rather complete consideration of these special problems.

The treatment of the various subjects considered in the volume in no sense can be termed mathematical. Nevertheless, the authors seem to have exerted a conscious effort to give concrete examples of limiting values. Reading, in general, is not difficult and most will find reading of the book a pleasure and not a burden. The writer of the review, a hydrologist who has studied geology, considers that the book merits a place in the library of every hydrologist and every geologist whose field is concerned with the work of water. Students of other sciences may find much of value in the book.

In summary, a phrase from the book is well worth considering. "Moreover, not being a geomorphologist he missed the point. . . . " It might be well said that a geologist who knows what is in this book is not likely to "miss the point" on any subject where water is related to geology.

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